Study of a new experiment for the search of $\nu_\mu - \nu_\tau$ oscillations

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ABSTRACT

We present the conceptual design of TENOR (Tracking and Emulsions for Neutrino Oscillation Research), a "short-baseline" experiment aiming at a new high sensitivity search for $\nu_\mu - \nu_\tau$ oscillations in the CERN Wide Band Neutrino Beam. We show that by exploiting the advances in the technology of nuclear emulsions, one can conceive a hybrid apparatus with an emulsion target a factor six heavier than the one presently used in the CHORUS experiment. The main features of the experiment are discussed, as well as the issues of data selection, background reduction, and sensitivity in the determination of $\sin^2 2\theta_{\mu\tau}$. The present estimates on the experimental backgrounds are extrapolated from those anticipated for the CHORUS experiment; a more thorough study is still needed. The expected sensitivity of the experiment on the oscillation mixing angle is more than a factor 15 higher than those of the present explorations. In the case of a negative search, and for large Δm^2 , the 90% CL upper limit in the mixing angle would be $\sin^2 2\theta_{\mu\tau} < 9 \times 10^{-6}$.

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1. Introduction

The question of a non-zero mass of the neutrino is one of the most crucial in the present scenario of particle physics. A massive neutrino would be the direct indication of some physics beyond the Standard Model. It would also be of extreme interest for cosmology and astroparticle physics, giving a clue in the explanation of the Dark Matter puzzle. Moreover, a neutrino non-zero mass could be responsible for the apparent deficit of solar neutrinos, advocating the process of neutrino oscillations in matter. A possible scenario, in the light of plausible theoretical assumptions and of the existing experimental results, tends to indicate very light electron and muon neutrinos, with a tau neutrino mass ranging from 1 to 10 eV as a natural candidate for the “hot” component of the dark matter.

The above mass range is out of reach for the present “direct” measurements. The only way to assess this issue is to perform neutrino oscillation searches. The oscillation mechanism also implies the mixing of neutrino species, and it is described in terms of a mixing angle and a mass squared difference. As an example, the present limits on the $\nu_\mu - \nu_\tau$ oscillations exclude mixing angle values $\sin^2 2\theta_{\mu\tau} > 5 \times 10^{-3}$ for mass differences $\Delta m^2 > 20 \text{ eV}^2$.

Presently, two collaborations at CERN, CHORUS [1] and NOMAD [2], are carrying out experimental searches for $\nu_\mu - \nu_\tau$ oscillations, with the aim of improving the existing limit on the mixing angle by more than an order of magnitude, extending the sensitivity on $\sin^2 2\theta_{\mu\tau}$ at the level of $\sim 10^{-4}$. It is evident that, in case of a positive signal, a new dedicated experiment of higher sensitivity would be needed to confirm the discovery and learn more. In case of a negative result, however, the present uncertainties on the theoretical speculations and on the indirect deductions from other experiments would suggest the further extension of the exploration to a mixing angle as low as 10^{-5} and to smaller masses, down to $\sim 1 \text{ eV}$.

In this paper we present a design philosophy based on hybrid detector techniques, give a tentative experimental layout, and estimate the sensitivity that can be reached by such a $\nu_\mu - \nu_\tau$ oscillation experiment (TENOR¹). The purpose is to show the feasibility of an experiment for a new, high sensitivity search for neutrino oscillations exploiting emulsions on an unprecedented mass scale. The emulsions will also be used in a novel application anticipated in Ref.[3], for particle spectrometry. The experiment we propose profits from the advances in the automatic scanning facilities and, in general, from the operation of nuclear emulsion detectors.

In the following, we discuss the conceptual design of TENOR, which leaves open options and detailed studies for the final design. We intend to show that, even exploiting existing accelerator facilities, like the CERN Neutrino Wide Band Beam,

¹Tracking and Emulsions for Neutrino Oscillation Research.

and complementing the emulsions with relatively standard (and in some options existing) electronic detectors, one may be readily able to perform a new generation, high sensitivity neutrino oscillation search.

This work benefits from a long-standing and fruitful debate inside the CERN neutrino community and in particular in the CHORUS Collaboration. Some underlying ideas [4][5][6][7] were presented and discussed in several workshops and informal meetings.

2. Design philosophy

Thanks to the direct observation of the τ -decay in the emulsions, CHORUS is a low background experiment. Its hybrid detector is composed of an active target made of nuclear emulsions, complemented by electronic devices, needed both for the event selection and the background subtraction. The experimental signature of the $\nu_\mu - \nu_\tau$ oscillation is the production (and the detection) of a τ lepton in the charged current interaction of a ν_τ in the emulsion target. The high spatial resolution of the emulsions allows one to detect the typical decay “kink” of the track of the short-lived τ . Scintillating fiber trackers permit the restriction of the scanning area, predicting the track position in the emulsion foil just upstream of them with a $\sim 200 \times 200 \mu\text{m}^2$ resolution.

The main task of the other electronic detectors (calorimeter and spectrometers) is to perform a kinematic preselection of the events. One can then retain, with an acceptable efficiency, interactions which are compatible with a ν_τ interaction, and reject most of the ordinary ν_μ induced events, prior to the (time-consuming) emulsion scanning. Obviously, the price that one has to pay, because of this preselection, is a lower signal efficiency. Once an interesting event is found in the emulsions, the electronic detector will help in the full kinematic analysis of the event.

For an experiment aiming at a considerable improvement in sensitivity with respect to CHORUS and NOMAD, we retain the emulsion technique, intrinsically powerful in the background rejection. The appreciable increase in the emulsion mass, which is required to meet the goal, is made possible by the progress under way in the automatic scanning facilities and, in general, in the operation of nuclear emulsion detectors. These advances makes it conceivable [8] to analyse the data of an experiment which uses an emulsion target even an order of magnitude heavier than the CHORUS target (0.8 tons). Member groups of the CHORUS Collaboration, namely the group of Nagoya, pioneer in the technique, and the group of Salerno, are presently carrying out intense R&D programmes on fully automated microscopes for scanning.

For a complete spectrometric analysis of candidate events, an important asset in controlling the background, we place the detector inside a uniform magnetic field, as already envisaged in Ref.[4]. This is possible if we give to the massive

emulsion target a modular structure (similar to the case discussed in Ref.[5]), with each module followed by tracking devices. The latter must have very high spatial resolution, in order to perform the momentum measurement in the relatively short drift space between consecutive modules. This leads to the choice of emulsions also for the tracking. In this philosophy, the role of the electronic trackers becomes limited, therefore, to the reconstruction and location in the emulsions of at least one track conveniently selected to attain the event vertex.

It appears difficult (and expensive) to equip a 5 ton emulsion mass, necessarily subdivided into stacks due to the small radiation length², with electronic detectors allowing kinematic cuts "à la CHORUS" for the event reduction. We thus assume running without cuts. On the other hand, we aim at reducing the scanning time, with respect to CHORUS, by means of an improved accuracy in the track prediction (smaller scanning area) and by relying on the advances in the automatic scanning techniques. The accent is on improving the scanning time per event rather than reducing, by kinematical cuts, the number of events to be scanned.

For the same reason that makes kinematic cuts by means of electronic detectors difficult, the kinematic analysis of the events reconstructed in the emulsions cannot be based on electronic devices. As already pointed out, emulsions have to be used also for this purpose, but only for candidate events, i.e. those showing a potentially interesting topology (a few per cent of the total, as discussed later on).

In CHORUS, besides bulk emulsions where neutrinos interact, one has emulsion sheets (ES), i.e. thin interface emulsion layers with the purpose of locating the tracks with high accuracy (once extrapolated from the fiber tracker) and measuring their slope, prior to the scan of the bulk emulsions. Because of their structure (100 μm thick emulsion layers deposited on both sides of a $\sim 800 \mu\text{m}$ plastic base) the ES give space points and directions.

In TENOR, a set of ES also provide full local information sufficient for the complete reconstruction of candidate events. They determine a local miniaturization of the event reconstruction in a massive and compact apparatus. We are therefore led to conceive a detector whose central body, completely contained in a magnetic field, consists of a sequence of emulsion stacks (bulks and ES) and electronic trackers, the latter having the task of precisely locating the follow-back track in the emulsion sheets. We observe that other past experiments, such as WA17 [9] at CERN, made use of emulsion stacks placed in an intense magnetic field with external tracking.

Apart from further optimizations, driven by the physics goal [6] and by the outcomes of a careful study of the relevant background sources, we consider the present CERN Wide Band Beam and the CHORUS location. The average muon neutrino energy is 27 GeV and the mean distance of the detector from the neutrino

²The radiation and the interaction lengths of emulsions are 2.89 cm and 38 cm, respectively.

source is ~ 0.650 km, leading to a so-called “short-baseline” experiment.

3. Detector layout

If we assume to start running after the completion of the CHORUS and NOMAD data-taking programmes, the emulsions and the tracking modules could be housed in the UA1 magnet, presently used by NOMAD. We observe that, apart from the target and the associated tracking detectors that are completely different here, UA1 and NOMAD have equipped the magnet with electronic detectors for calorimetry, muon tracking and triggering, which can be partly used in TENOR. Other possibilities were considered in Ref.[4].

In the NOMAD experiment, the UA1 magnet provides a 0.4 T dipolar field over a $3.5 \times 3.5 \times 7$ m³ inner volume. However, it can be operated up to 0.7 T. The magnet can be completely opened for the installation and for the maintenance of the detectors. The space really available for the TENOR inner detectors is somewhat smaller, because the magnet must also to contain the “cool box”, where the emulsions have to be placed to prevent fading, namely the progressive erasing of the latent image. The magnet would be installed with the field vector horizontal and orthogonal to the beam direction, as in the case of NOMAD.

Each CHORUS bulk emulsion stack has 2.75 cm emulsion thickness and 1.44×1.44 m² cross-section, weighing approximately 0.2 tons. In TENOR, a 1.64×1.64 m² stack 5 cm thick³, still less than two radiation lengths, is worth in mass more than two CHORUS stacks. An increase of the emulsion mass by about a factor 6 (up to 4.7 tons) is given by 10 of such stacks. A 6 m total length available for the target implies that, longitudinally, about 60 cm are available for each bulk emulsion stack and the associated emulsion and electronic trackers, from now on called a detector “module”. This could then consist of:

- one bulk emulsion stack;
- a triplet of ES;

one ES is placed just behind the bulk emulsion stack, a second one is located immediately in front of the following bulk emulsion stack, and a third is placed in the middle plane between the first two (lateral) ES. The middle ES determines a high precision space segment; this information, combined with that from the other two ES, allows momentum analysis by means of a sagitta measurement in the gap between consecutive stacks⁴. The first ES also has the additional task of precisely locating the track in the bulk emulsions.

- electronic trackers;
- a pair of silicon detector planes placed behind the first ES, to improve the

³Emulsion stacks 5 cm thick are being considered by the COSMOS Collaboration at Fermilab [10].

⁴As discussed in the following, because of multiple scattering, one must exclude the bulk emulsions for the momentum measurement.

track location in this emulsion sheet;

- trigger devices (for some of the modules only).

The transverse dimensions of each ES plane have to be larger than those of the bulk stack, in order to reconstruct efficiently the tracks originating in the entire target volume; we assume therefore an ES surface of $1.8 \times 1.8 \text{ m}^2$.

There are conventional options for electronic tracking, in particular straw tubes or honeycomb chambers. The JETSET Collaboration at CERN has constructed a barrel chamber using 8 mm diameter straw tubes [11]. The SDC detector for SSC had foreseen [12] straw tube modules with eight planes of 5 mm diameter tubes, enclosed in a carbon fiber shell and operating in a 2 T axial field. Honeycomb drift chambers with 5 or 10 mm cell diameter have been envisaged for the HERA-B outer tracker [13] and for the ATLAS detector at the LHC [14]. However, other tracking techniques may be considered as options.

The two single-sided silicon planes (or one double-sided plane) are placed immediately behind the most upstream ES in each TENOR target module, and constrain the track extrapolation to this ES with a high accuracy space point. This implies, as we will see later on, a substantial decrease of the ES scanning surface, thus drastically reducing the scanning time.

A possible layout for the TENOR target is shown in Fig. 1. A module is equipped with eight electronic multilayer trackers, each about 4 cm thick and measuring one of the x,y or inclined (u,v) coordinates, with the three ES described above, and with the two silicon detector planes. Each tracker comprises four planes of 10 mm diameter straw tubes, 1.80 m long. The total number of tubes in the tracking system is about 50000. Given the relatively low occupancy generated by neutrino events, multiplexing could provide a substantial reduction of the number of the electronics channels. Trigger detector planes could be inserted behind some of the modules.

The total silicon detector surface, corresponding to two single-sided planes for each of the ten modules, is about 50 m^2 . This is a large area, compared with existing detectors of this kind, but not unrealistic. In fact, the advances in the production of low-cost and large-surface silicon detectors and in the associated electronics [15], makes the above design conceivable in terms of realization, operation and cost. Indeed, other authors [7] have recently proposed, for neutrino oscillation experiments, the use of large-surface silicon detectors to apply impact parameter techniques to the study of the neutrino interaction vertex. Ref.[7] also gives the possible design features of the silicon tracker.

4. Electronic tracking

The drift time measurement in a straw tube gives a spatial resolution of the order of 100-150 μm for each single tube. By means of four layers, each consisting of

10 mm diameter tubes, it should be feasible to predict the track location in the ES with an accuracy of about $100\ \mu\text{m}$, including systematic errors and the effect of the magnetic field. This accuracy further improves when the high accuracy point given by the silicon detectors is included. For the latter, the expected space resolution is at the level of $5 \times 5\ \mu\text{m}^2$. An overall precision of about $20\text{-}30\ \mu\text{m}$ in the determination of the ES track impact point should be feasible, even when systematic errors are included. This is equivalent to a reduction of the ES scanning area by more than a factor 100 with respect to CHORUS, a factor which well balances the increase of the scanning time caused by releasing the kinematic cuts.

It is important to stress again that electronic trackers, together with the high-precision silicon detectors, have the primary task of following back one or two appropriately selected tracks into the ES just upstream. From this point one can proceed to the location of the vertex of the interaction in the bulk emulsions. An isolation criterion can enter in the choice of the track(s) to be extrapolated back into the ES. For this reason, the two-track resolution is less important than at first sight appears.

The magnetic field, needed to study the kinematics of candidate events by means of the ES, affects the tracking and the event reconstruction procedure. Since each electronic tracker consists of four planes, they define track segments so that one can follow the trajectories with continuity, although in different projections. Detailed simulations will allow us to define the optimal detector configuration and granularity, on account of the difficulties of tracking in the magnetic field and of the requirements of the two-track resolution.

The complete reconstruction is performed only for a relatively small number of candidate events. The electronic trackers establish a road which helps in connecting the track segments in the three ES of the module. This is done prior to the momentum analysis, performed for all the tracks in the event.

5. Momentum measurement

Each ES should give an angular accuracy of about $0.7\ \text{mrad}$, which, in a deflection measurement, adds in quadrature to $1\ \text{mrad}$. In the CHORUS experiment, a pair of emulsion sheets (analogous to the ES) give an accuracy one order of magnitude better than the one obtainable within the bulk emulsions. In TENOR, as an example, we could determine the momentum by combining the track angle measurement with the two lateral ES alone in the $0.7\ \text{T}$ magnetic field. Thus, we obtain a momentum resolution:

$$(\Delta p/p)_{\text{meas}} = 0.9\% \times p[\text{GeV}/c]$$

in addition to a 2% contribution from the multiple scattering in the ES and in the electronic trackers (the latter about 0.032 radiation lengths thick [12]). This

in absence of the middle ES plane, which is not needed for such a momentum measurement.

The use of the middle, together with the two lateral ES, further improves the resolution. In such a way, we measure three space points (segments) along the track, with high accuracy. The relative alignment of the ES is performed using high-energy halo muons, and the alignment methods (and their requirements) have to be studied carefully. Assuming a precision ($5\text{ }\mu\text{m}$) about a factor five worse than the intrinsic resolution of the emulsions, and given the 51 cm distance between the lateral ES, we obtain a momentum resolution:

$$(\Delta p/p)_{meas} = 0.08\% \times p[\text{GeV}/c].$$

The multiple scattering in the lateral ES does not appreciably affect the measurement of the track coordinates at their location, hence the sagitta measurement. Taking into account the multiple scattering in the electronic trackers, in the silicon planes ($2 \times 300\text{ }\mu\text{m}$ of silicon, i.e. 0.007 radiation lengths) and in the central ES (100 μm emulsions and 800 μm plastic base, i.e. 0.006 radiation lengths), the total contribution of the Coulomb scattering to the momentum resolution amounts to about:

$$(\Delta p/p)_{MS} = 2.5\%.$$

By combining quadratically the position measurement and the multiple scattering contributions, we obtain the global momentum resolution shown in Fig. 2. One can see that, in the momentum range of interest, the Coulomb scattering is such that the resolution does not depend critically on the assumed measurement errors. Since the resolution term due to the position measurement increases linearly with the space point uncertainty, even in the conservative case of a 20 μm precision, the total momentum resolution stays below 10% up to 30 GeV/c. The requirements on the relative ES alignment and on the spatial resolution thus appear to be within the experimental capabilities.

One bulk emulsion stack (5 cm) corresponds to 1.73 radiation lengths and 0.13 interaction lengths. Multiple scattering gives, in this case:

$$\Delta\theta = 18\text{ mrad}/p[\text{GeV}/c].$$

Therefore, the information from ES in different modules cannot be used in a global analytical fit giving the particle momentum. One can, however, average the momentum measurements in two or more subsequent modules traversed by the track, thus substantially improving the resolution relative to the one quoted above. Owing

to the low interaction probability in a single bulk stack, this is actually feasible for most charged hadrons.

In Fig. 3 we show a Monte Carlo simulated event where a ν_τ , interacting in an emulsion stack, produces a τ lepton, which in turn undergoes a muonic decay.

6. Other detectors of the apparatus

Apart from the precise spectrometric measurement of charged particle, performed with the emulsion sheets, one has also to detect neutral particles. For this purpose, downstream of the last target module and inside the magnet, a calorimeter allows the detection of neutrals; this is straightforward for those events occurring near the downstream end of the target.

The UA1 magnet yoke was equipped with scintillators for a calorimetric measurement of the hadrons with standard resolution ($100\%/\sqrt{E}$). This set-up can be adopted for the downstream yoke, with the primary task of discriminating hadron punchthroughs against muons.

Neutral particles produced in neutrino events may interact in the emulsion material downstream of the primary vertex. The tracking system then allows the determination of their interaction point, needed for the global event reconstruction. The periodic structure of modules (emulsion and electronic trackers as active elements) also acts as a coarse sampling calorimeter, to measure the energy deposit of neutral particles. A similar configuration is exploited in the CHORUS experiment: the emulsion stacks act as the passive material of a calorimeter where the scintillating fiber trackers represent the active medium. This allows one to estimate the energy lost in the target before the fine sampling by the lead-scintillating fiber calorimeter.

In TENOR, external to the magnet, a forward muon detector also provides the trigger for quasi elastic and charged current events. Resistive plate chambers (RPC) or scintillator planes are options for the muon trigger, and the existing UA1 drift chambers may be used for the track reconstruction. Muon detection at large angles can be provided by muon chambers inserted in the magnet yoke. Their information may be combined with that from tracking and momentum measurement inside the magnet.

Given the spatial extension of the emulsion target, the experiment may require a distributed neutrino interaction trigger. An option to be studied foresees the use of RPC chambers, inserted in the target. Alternatively, scintillator planes can be used for this purpose.

Finally, a veto system and an upstream calorimeter have to be included in the apparatus to veto incoming muons and neutrino interactions in the magnet yoke. A solution similar to the one adopted by CHORUS and, in particular, NOMAD can

be envisaged.

7. Feasibility of a 5 ton emulsion target

The CHORUS Collaboration already envisaged (for a possible future experiment) the idea of alternating emulsion sheets with thin heavy passive material foils [5][6], in order to obtain a high fiducial mass reducing the amount of (expensive) emulsions. This option could bring an increase in the background due to the reduced capability of direct detection of the decay. However, given the good expected performance of the TENOR detector in the kinematic analysis of the events, even in this case the background could possibly be kept relatively low.

Let us, however, assume the design of the experiment with a fully active 5 ton target, which seems to be realistic, as shown below.

Handling of such a huge quantity of nuclear emulsions is a big challenge, but several hybrid experiments were run for more than 20 years both at CERN and Fermilab and this allowed refinement of the technique. The main problems to be faced (apart from those related to the analysis, considered later on) are:

- The production of raw material (emulsion gel), with high and uniform sensitivity and good stability, within a reasonable period (6 to 12 months) and at a convenient price. Some time ago, close contacts with large firms were established and several tests are now under way jointly with them. Some points are still open, but the residual problems could be solved in due time. Concerning the emulsion cost, a reduction of at least a factor two with respect to the present one seems feasible.

- The preparation of the emulsions before the exposure (pouring and assembling into stacks). The most serious problem is represented here by the time needed for pouring, i.e. for producing the final emulsions from gel. With the presently available facilities, the procedure would take too long (of the order of one year) and would require too much manpower. We are studying alternative solutions, either based on a new laboratory, with greater resources and mostly automated, or giving the job to the producers of gel, after having carefully agreed upon the specifications and under our supervision. No particular problem is anticipated for the assembly.

- The processing of the emulsions after exposure. Here, again, the present structures would lead to a prohibitively long processing time, and therefore we are studying the design of a new automated laboratory. Apart from this requirement,

no serious uncertainty can be foreseen.

8. Data

In CHORUS, the kinematic cuts applied to reduce the scanning load also reduce the detection efficiencies by appreciable amounts, as indicated in the proposal [1]. In the following, we list the cut efficiencies (i.e. the fraction of τ events surviving the kinematic cuts) for the three main decay channels of the τ in CHORUS:

Decay channel	BR	Cut efficiency
μ	0.178	0.72
π	0.500	0.33
3π	0.138	0.70

If kinematic cuts are not applied and we also consider, according to preliminary estimates, an average increase of the efficiencies of about 40% mainly due to the higher geometric acceptance of TENOR, the products BR $\times$ eff. (also taking into account the ratio of the tau neutrino to muon neutrino cross-sections) scale as follows:

Decay channel	CHORUS	TENOR
μ	$0.178 \times 0.098 = 0.0174$	0.036
π	$0.500 \times 0.046 = 0.0230$	0.098
3π	$0.138 \times 0.065 = 0.0089$	0.018
Total	0.0493	0.152

An additional contribution of 0.045 is expected to come from the quasi elastic events and the τ decays into electrons. The quasi elastic events (with the τ produced with small recoil) and the electron decays of the τ , are presently being studied by the CHORUS Collaboration, although not considered in the proposal. This could bring the total BR $\times$ eff. of TENOR to about 20%, thus improving over CHORUS by a factor 4.

In CHORUS, the main limitation to the total exposure time of the emulsions comes from the muons associated with the SPS X7 test beam in the West Area. They overwhelm other background sources and affect the event visibility in the emulsion scanning. The X7 beam should run at low energy or (possibly) be shut down. A three year emulsion exposure is, in this way, foreseeable.

For obvious reasons of cost the 5 ton emulsion target cannot be replaced, as was done with the CHORUS target for the two-year extension of the data taking:

the request of intensive 200 days/year SPS neutrino runs is therefore justified.

In 1995, its second year of running, CHORUS collected 2.2×10^5 charged current events in about 150 days. The SPS and CHORUS efficiencies were 72% and 88%, respectively. An experiment where the emulsion cost is large must take data when it has already reached a good efficiency, after an adequate running period essentially with electronic detectors alone. Therefore, let us take the above performance as a basis for discussion.

Accounting for the emulsion mass increase from 0.8 to 4.7 tons, for an increase of the proton intensity on the target by a factor 1.5^5 and for 200 days/year of running with the above efficiencies, the collection of about 7.7×10^6 charged current events in three years can be taken as a working hypothesis.

9. Emulsion scanning

The scanning capability now achieved by CHORUS is about 10^3 events / (month $\times$ microscope), including the downtime. Most of the scanning time goes into the analysis of the ES downstream of the bulk emulsions. In fact, thanks to the ES, the tracks in the bulk emulsions can be located with a micrometric accuracy. The complete emulsion scanning and event reconstruction is performed only for those events with a decay topology (tau or charm decay).

As already discussed, we aim at an improvement of the scanning time with respect to CHORUS, due to a more accurate prediction of the track coordinates in the emulsions. A reduction of about a factor 100 in the ES surface to be scanned is achieved thanks to the precise predictions of the silicon detectors. This drastically reduces the time needed to scan the ES. Moreover, the technique of automatic emulsion scanning is still undergoing considerable progress, and an increase in the scanning speed by a factor 2-3 is reachable. This will lead, eventually, to a speed of one microscope field scanned in less than five seconds.

Let us assume that 20 microscopes (not far from what is foreseen for CHORUS) can be routinely operated with the tools and the experience now being gathered. With the improvements quoted above, a scanning capability of about 3×10^6 events/year is possible, also accounting for bulk emulsion scanning. As already pointed out, the scan of the two downstream ES in a module, as well as the ES in the other modules where the tracks can be followed up, will be done only for candidate events.

Even disregarding kinematic cuts, the scanning of 2.5×10^6 muonless and 7.7×10^6 muonic events appears feasible in three years after the end of the data taking. In that sample, the fraction of events to be completely reconstructed can be estimated, from charm production, to be about 5%. We note that, since the ES

⁵In 1995, the nominal neutrino beam intensity has been 2×10^{13} protons/cycle; it was shown that an intensity of 3×10^{13} protons/cycle can be accepted by the proton target.

are replaced after each year of running, their scanning can proceed in parallel with data taking.

10. Sensitivity of the experiment

Let us now focus our attention on the main backgrounds quoted in the CHORUS proposal. At the level of sensitivity aimed at, backgrounds which are negligible in CHORUS may become, however, significant and deserve a careful study. In particular, this is the case for the prompt ν_τ background, which, according to recent calculations [16] appears to be higher than originally foreseen, and at a level to be relevant for TENOR.

The total number of background events expected by CHORUS in the μ , π and 3π channels is 1.7 for 5×10^5 charged current events. The CHORUS proposal [1] anticipates a further background reduction by a factor 5 by the study of the vertex kinematics of the final candidates, with 80% efficiency for the signal. However, by better exploiting the vertex kinematics one can aim at a background reduction by a factor 50 (10), still retaining 60% (80%) of the signal [17]. In TENOR, the geometric acceptance is higher and the target is fully immersed in a magnetic field, allowing for a better spectrometry of the full event. Let us make the relatively conservative assumption that the experiment will reach a factor 30 in the background reduction, with a signal efficiency $e_{kin} = 60\%$.

With 7.7×10^6 charged currents, the number of background events then scales from 1.7 to 3.3. To a first approximation, we assume that in TENOR the global increase in the efficiency raises the number of background events in the same proportion (about a factor 4) as for the signal. By inspecting the appropriate tables in the CHORUS proposal and focusing attention on the dominating backgrounds, this rough assumption appears to be acceptable. If TENOR really observes 3 events, the upper limit given to a neutrino oscillation signal would correspond to 4.3 events at the 90% CL [18]. The sensitivity limit at large Δm^2 would then be:

$$\sin^2 2\theta_{\mu\tau} < 2 \times 4.3 / (BR \times eff. \times e_{kin} \times N_{CC}) \sim 9 \times 10^{-6}$$

with the minimum Δm^2 (i.e. for maximal mixing) equal to 0.09 eV².

As a comparison, CHORUS should reach a limit of about 1.5×10^{-4} in four years of running. The Fermilab experiment COSMOS, also using emulsions as a target and expected to start data taking in the year 2002, aims at a sensitivity of 2.8×10^{-5} [10]. This result could be attained under the assumption of excellent performance of the future Main Injector, and eight months/year of beam-time for four years. Fig. 4 shows an exclusion plot where the expected sensitivity of TENOR is compared with that of other experiments.

An alternative design is possible which does not foresee silicon planes in

the apparatus. Indeed, in Ref.[3] we have shown that one can reach a comparable sensitivity by exploiting a heavier emulsion target of about 8 ton, and disregarding, in a first approach, the deep inelastic muonic decay channel. In this way one keeps the number of events to be scanned at a reasonable level.

Finally, we stress that the proposed experiment can make use of an existing beam facility, based on an accelerator having stable and high performance. In the present estimates we have not yet taken into account neither improvements of the CERN Neutrino Beam, such as those envisaged by the CHORUS Collaboration for the future of neutrino physics at CERN [6], nor modifications possibly required to cope with the prompt ν_τ background.

11. Conclusions

We have presented the conceptual design of TENOR, a new high-sensitivity short-baseline experiment to search for $\nu_\mu - \nu_\tau$ oscillations in the CERN Wide Band Neutrino Beam.

The experiment exploits the emulsion target technique on an unprecedented scale (about 5 tons of emulsions) for the direct observation of the τ lepton decay in ν_τ charged current interactions. The experiment takes advantage of the continuous progress of the technique of automatic emulsion scanning, with the prospect of the analysis of a large number of events in an acceptable amount of time.

The bulk emulsion target and the electronic tracking system, needed for the event location in the interface emulsion sheets, are placed in the 0.7 T dipolar field of the former UA1 magnet. The electronic trackers may be straw tubes, honeycomb chambers, or equivalent detectors. The extrapolation of the tracks into the ES which is close to the bulk emulsion in a module exploits the high space resolution of silicon detector planes. The development of this technique, its performance, and the foreseen cost reduction make it realistic to design silicon detectors with a large total surface, as in the case of TENOR.

The reconstruction of the candidate event kinematics is performed with high accuracy (and in a limited drift space) by means of emulsion sheets, the most upstream of each target module also being used to locate the interaction vertex in the bulk emulsions.

In addition to the UA1/NOMAD magnet, other components of the apparatus already exist. External to the magnet, drift chambers provide muon detection, together with other chambers inserted in the iron of the magnet. RPC (or scintillator) planes placed along the emulsion target may constitute the distributed trigger system. The sequence of emulsion stacks and electronic trackers allows neutral particle detection, together with a calorimeter placed at the target end, inside the magnet. The forward yoke calorimeter performs the discrimination of punchthrough hadrons against muons.

The estimate of the sensitivity is based on first-approximation assumptions on efficiencies and backgrounds, driven by the experience of the CHORUS experiment. Detailed Monte Carlo simulations will allow an assessment of the expected performance of the apparatus and of the backgrounds, this being in particular needed for the background originating from prompt tau neutrinos in the beam. In the case of a negative search in the existing CERN Wide Band Beam, the limit (90% CL) for large Δm^2 is:

$$\sin^2 2\theta_{\mu\tau} < 9 \times 10^{-6}$$

while the minimum Δm^2 (i.e. for maximal mixing) is 0.09 eV². The above limit in the mixing angle is more than a factor 15 better than the expected CHORUS result in the absence of a positive signal, and a factor 3 more sensitive than the one obtainable by the proposed COSMOS experiment at the future Fermilab Main Injector.

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Figure 1: Side view of the TENOR detector layout.

Figure 2: Momentum resolution obtained in a single target module. The resolution is shown for different measurement errors. The contribution of the multiple scattering (MS) alone is also shown.

Figure 3: Monte Carlo simulation of a $\tau \rightarrow \mu$ event, generated in the TENOR target.

Figure 4: Exclusion plot showing the expected TENOR sensitivity.