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Physics Justification for a Hybrid Emulsion Detector in MINOS

The MINOS Collaboration

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Introduction

In April 1999, the MINOS Collaboration submitted a proposal to the Fermilab PAC for support of an R&D effort leading towards construction of a hybrid emulsion detector (HED) in MINOS. This proposal put forth the physics justification for such a detector addition and outlined the necessary R&D work. We understand from the Fermilab Directorate that the PAC has not yet had an opportunity to discuss this proposal in any detail. In letters of July 22 from Mike Witherell and of September 21 from Mike Shaevitz, we have been asked to elaborate further on the physics case for such a detector, especially in light of increased interest in using it to search for $\nu_\mu \rightarrow \nu_e$ oscillations. This note attempts to address that request.

We would like to start out with few words about the philosophy of this document. First, we do not want to repeat most of the information contained in the April Proposal, and refer the readers to that document for additional details. Following the request from the Directorate, we shall focus on the physics case. Second, we emphasize that the discussion below is in the context of an R&D proposal. Thus there are a number of issues that are still unresolved and we hope that the ensuing R&D effort will be able to clarify them.

General Discussion

Our physics interest in investigating the possibility of a hybrid emulsion detector is centered around two oscillation channels: $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$. We would like to study both of these processes in the Δm^2 range suggested by the Super-Kamiokande experiment on the atmospheric neutrinos.

The currently favored scheme for explaining the atmospheric and solar neutrino results invokes three neutrino mass states. Two of these, ν_2 and ν_3, are dominantly ν_τ and ν_μ with roughly equal mixtures of each, and with a mass difference between them characteristic of atmospheric neutrino anomaly. The third mass state, ν_1, is almost degenerate with one of the other two mass states - the mass difference being small and characteristic of the solar anomaly. In some models, like the solar small-angle solution, this mass state is primarily ν_e. This picture does not attempt to account for the LSND effect.

Thus, in this picture, we have a mass hierarchy:

$$m_1 < m_2 << m_3, \text{ with } \delta m^2 \text{ (solar)} \equiv m_2{}^2 - m_1{}^2 << m_3{}^2 - m_2{}^2 \equiv \Delta m^2\text{(atmospheric)}.$$

Full understanding of neutrino oscillations requires the determination of the full neutrino-mixing matrix, just as understanding the quark sector requires determination of the CKM matrix. This requires measuring the three mixing angles - usually referred to as θ_{12}, θ_{23}, and θ_{13}, as well as the phase specifying the amount of CP violation. The last parameter is beyond the reach of currently planned experiments. The first angle, θ_{12}, determines the behavior of solar neutrino oscillations and, according to the current data, could either be in the 10^{-3} - 10^{-2} range (small angle solution) or near 90 deg (large angle solution).

In the hierarchical mass-structure picture described above, the $\nu_\mu \rightarrow \nu_\tau$ oscillation probability is given by:

$$P(\nu_\mu \rightarrow \nu_\tau) \propto (s_{23} \times c_{23} \times c_{13}{}^2)^2,$$

using the conventional notation $s_{ij} = \sin(\theta_{ij})$, $c_{ij} = \cos(\theta_{ij})$. If the Super-K observation is to be explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations, then θ_{23} must be close to 45 deg and θ_{13} must be relatively small. The best way to measure this angle is to study $\nu_\mu \rightarrow \nu_e$ oscillations in the region characterized by the Δm^2 of the atmospheric neutrino anomaly. Again, under the same assumptions about the mass pattern, this probability is:

$$P(\nu_\mu \rightarrow \nu_e) \propto (s_{23} \times c_{13} \times s_{13})^2.$$

Thus the $\nu_\mu \rightarrow \nu_e$ oscillation search probes directly the third angle of the neutrino-mixing matrix.

We must emphasize that determining whether the conventional picture does indeed correspond to reality is an experimental question. There is no one particular accepted theory that provides reliable guidance as to what the mixing angles should be in the neutrino sector. The analogy with the quark sector does not appear to provide us with the correct picture. Clearly, if the neutrino picture needs to be extended beyond the three-flavor scenario, the spectrum of possibilities for different mixing angles increases dramatically. We feel that good measurement of the two oscillation channels discussed here will be very important in our efforts to understand the neutrino sector.

The argument for using emulsions as a detector for ν_τ's is relatively straightforward. Emulsion is probably the only practical medium that is capable of identifying τ's in a neutrino experiment on an event by event basis. Its important positive feature is its superior position resolution. To date, its negative features have included its expense and the very labor-intensive effort required to produce and develop the emulsions, as well as to analyze the data. Over the past several years a number of important advances in the areas of emulsion production technology and automatic scanning techniques have been employed to mitigate these historical drawbacks. In addition, it is important to keep in mind that the expected number of interactions in an oscillation experiment will be relatively small, so that data analysis should be very manageable. Our pursuit of this effort tries to be responsive to several previous recommendations of the PAC which have stressed the importance of identifying ν_τ's on an individual event basis.

The suitability of emulsions for detection of ν_e events is less obvious. But a close examination of the problems connected with identifying oscillated ν_e events at a low level in the MINOS experiment leads us to believe that an emulsion detector might be an optimum, and most cost effective, means of searching for this process. An important potential advantage of an emulsion detector could be its superior ability to suppress and/or reject certain backgrounds that could limit the potential sensitivity of this search. More extensive calculations, anticipated as part of the proposed R&D program, are needed to establish whether this is indeed a valid statement.

We anticipate that a small HED will be placed in the NuMI near detector hall at Fermilab to provide direct measurements of backgrounds for both ν_e and ν_τ, and also of beam and detector characteristics. These measurements will be crucial in verifying the performance of various analysis cuts to be applied to the far detector data sample. Furthermore, the fact that we can quickly obtain a significant number of emulsion events in the near detector location will allow us to initiate, debug and understand the emulsion scanning and measuring process in the early stages of the experiment.

The combination of the HED and the main MINOS detector, both present in the near and far locations, will form a powerful instrument to study neutrino oscillations. The complementarity of the two techniques will allow us to perform a mutually constrained set of measurements, which would not be possible with a single detector.

The performance of HED as a ν_τ or ν_e oscillation detector is clearly closely coupled with the energy of the beam and the physics parameters of the oscillation processes. The initial running energy of the MINOS experiment will be chosen to optimize the physics output of the main MINOS calorimeter and any other auxiliary detectors, in light of the physics knowledge available at the time this decision has to be taken. In this document we try to anticipate the most likely scenario and frame our physics arguments with such a scenario in mind. We are mindful, however, of the importance of maintaining maximum flexibility for as long as possible.

The $\nu_\mu \rightarrow \nu_\tau$ oscillation channel

The current Super-Kamiokande data strongly suggest the presence of ν_μ oscillations, characterized by a value of Δm^2 in the 1-8 $\times$ 10^{-3} eV^2 range (with the most likely value at 3.2), and the final state being either ν_τ or $\nu_{sterile}$. Clearly the ν_τ hypothesis conforms more to conventional ideas. In addition, there is mild experimental evidence now from the Super-K data itself for the dominance of the ν_τ final state. This evidence, at about the 2 σ level currently, is based on the analysis of the data for possible matter effects in the earth, expected to vanish for $\nu_{sterile}$, and on the observed ratio of NC/CC events.

The MINOS calorimeter data should be able to provide information on the oscillation mode through various statistical analyses, several of which have been described in the original MINOS proposal and in subsequent NuMI notes. These analyses tend to provide unambiguous mode discrimination only for the higher range of the currently allowed Δm^2 values.

The identification of the ν_τ final state should be rather unambiguous in an emulsion detector. In addition, very importantly, if τ detection can be made essentially background free, the improvement in sensitivity to low values of Δm^2 can be made more economically than for a statistical analysis. More specifically, sensitivity to low Δm^2 for the statistical analyses improves only as the 4^{th} root of the detector mass (or running time or number of protons on target); for a background free signature this dependence goes as the square root.

The above arguments point out that the strength of the physics case for an emulsion detector to identify ν_τ's will depend on several factors. The most important of these are:

a) The strength of evidence, from the Super-K experiment, for one or the other hypothesis. Clearly, if the situation is still indefinite a few years from now, the case for stressing direct ν_τ identification will be very strong.

b) The mode favored by the Super-K experiment. If the results indicate only a relatively low fraction of the final mode is due to ν_τ's, an emulsion experiment becomes important since it would be able to directly pinpoint, with an appearance experiment, the ν_τ fraction.

c) The value of Δm^2 as indicated either by the Super-K data, the K2K experiment, or the initial MINOS data. A value at the low end of the range would provide a strong argument for an emulsion addition, since the statistical analyses of accelerator experiments would be less definite on this point.

d) New unexpected information, either theoretical or experimental. The field of neutrino oscillations is quite new, at least from the experimental point of view. Even the current results, indicating large mixing, are quite surprising and would not have been anticipated by most people a decade ago. Thus we must be prepared for other possible surprises and should not foreclose new experimental options at this time.

The $\nu_\mu \rightarrow \nu_e$ oscillation channel

Currently the best limits on this oscillation mode come from the CHOOZ experiment, searching for the disappearance of ν_e's from a reactor, and from phenomenological analyses of all available neutrino oscillation data under the assumption of three mass states. The current CHOOZ limit on $\sin^2 2\theta$ (using a two-state analysis) is about 6-12% in the Super-K suggested Δm^2 range. Appearance experiments will be needed to improve this limit further. The goal of our $\nu_\mu \rightarrow \nu_e$ search is to probe this specific question.

In evaluating the MINOS HED physics case for this mode one must address two issues:

a) How well can an HED of reasonable size (and reasonable cost) perform this search (or measurement)?

b) How does the HED capability compare with what could be achieved with either the main MINOS calorimeter or with the Soudan 2 detector?

At the present time we only have rough answers to these questions; obtaining more definitive answers is one of the goals of our proposed R&D program.

To address these issues one has to consider potential backgrounds to the $\nu_\mu \rightarrow \nu_e$ search and understand the ability of different detecting methods to deal with them. The dominant backgrounds are:

a) The intrinsic ν_e component in the beam. Our beam studies indicate that the percentage of this component increases slightly as the NuMI beam energy is lowered, from 0.6% for the high energy beam to 1.5% in the low energy beam. The spectrum of this component, however, is quite distinct from the spectrum of the expected oscillated ν_e's. As an example, in the low energy beam, for $\Delta m^2 = 3.2 \times 10^{-3}$ eV^2, 90% of the oscillated signal is due to neutrinos with energy below 5 GeV, while 80% of the beam ν_e component is above 5 GeV. Thus energy resolution in the few GeV range is a very important characteristic of an optimum detector. The ν_e spectrum can be measured with good statistics in the appropriate near detector.

b) The $\tau \rightarrow e$ decay mode events, with τ's from ν_τ's produced via oscillations. Clearly, the importance of this background increases significantly with increasing energy due to τ-production energy threshold and ν_τ CC cross section energy dependence. It can be suppressed if a detector has the capability to either observe τ decay kinks or determine whether the electron comes from the primary vertex. In addition, these events will display a P_t imbalance (due to the two neutrinos in the decay) and a relatively lower energy of the electron.

c) NC events with a π^0 whose decay gamma(s) convert close enough to the vertex within the spatial resolution of the detector. These events will also have a P_t imbalance (due to the scattered neutrino) and generally the energy of the electromagnetic component will be rather low. The ability to identify the fact that a "track" has double ionization (due to e^+ and e^-) could also provide some suppression here.

d) NC events with Dalitz decays of the π^0. This component should be significantly lower than c) and is probably negligible.

e) Charm production followed by electronic decay. This component may become significant at higher energies (the charm cross section is not known very well in the 10-20 GeV range) but is probably not significant in our case.

Based on the above discussion we can identify the important components of a good ν_e detector:

a) Ability to identify a track as due to electron,

b) Good measurement of total energy of the event,

c) Good measurement of the energy of the electron,

d) Good measurement of the ionization of each track,

e) Good longitudinal granularity (fraction of a radiation length),

f) Good spatial resolution,

g) Good momentum imbalance measurement capability,

h) Large mass.

Except for the last factor, an emulsion detector appears like the ideal instrument but one needs a detailed quantitative comparison of various possibilities. We also need to obtain a better understanding of emulsion's ability to identify electrons, measure their energies, and measure the energy of the total event. The important positive factor here is that the experiment requires the detailed analysis of a relatively small number of events. Thus one can contemplate measurement processes which are relatively labor intensive.

The ability of the MINOS calorimeter to identify $\nu_\mu \rightarrow \nu_e$ oscillations has been studied by our Collaboration some time ago. Levels of a few $\times 10^{-3}$ in $\sin^2 2\theta$ could be reached for large Δm^2 with the high-energy beam. These studies need to be extended to small Δm^2, low-energy beams, and must include ν_τ -ν_e discrimination capability.

The Soudan 2 detector would have a fiducial mass for ν_e detection somewhere between 500 and 800 tons. This should be compared with a potential HED total mass of one or two hundred tons at the start of the run and increasing eventually up to about 1 kiloton. The use of Soudan 2 in this application would necessitate moving several (probably at least six) of the 4.5-ton modules from the Soudan mine to the near detector hall. New electronics would have to be developed, built, and installed for the near hall modules. The very fine longitudinal granularity of the Soudan 2 detector (on the average about 0.15 rl) and its low density are well matched to ν_e identification. Its transverse granularity, determined by anode wire spacing and cathode pad size, is around 1 cm, i.e., significantly worse than one could obtain with emulsion, but better than the main MINOS detector.

Detailed studies of these different possibilities have been initiated and will continue as part of the R&D program. We will present some preliminary results at the November PAC meeting. It is possible that similar sensitivities can be obtained with all three of these detectors. In light of the expected small ν_e signal and other intrinsic difficulties, we believe that the ability to make measurements with different techniques, with quite different experimental characteristics, is a goal worth pursuing.

Possible strategy for evolution of the program

Our capability to perform ν_τ and ν_e measurements is very closely coupled to the beam energy. The rate for ν_τ detection increases as the beam energy increases in the NuMI energy range (see attached NuMI-E-525), even for relatively low Δm^2. On the other hand, ν_e detection is done best at the lower beam energies because of higher oscillation probabilities, smaller τ background, and probably better total energy measurement in an emulsion detector (if performed using the Coulomb scattering method).

The above would argue for emphasizing ν_e detection during the early running, if indeed the MINOS experiment will start with the medium or low energy beam. We feel, however, that in this case the design of the ν_e emulsion detector should be such as not to prejudice its ability to detect τ's in the later stage of the program. The challenge of the design is thus to have a detector early in the run that meets the following goals:

a) Is large enough so that significant physics could be accomplished with it (100-200 tons),

b) Is sufficiently inexpensive so that it could be in place for early running (<$5M of MINOS project funds),

c) Its ability (per dollar spent) to detect τ's would not be much worse than an idealized ν_τ detector,

d) Does not deviate significantly in important technology or construction techniques from an ideal τ detector that might be constructed later to complete the HED.

Our current R&D program addresses these goals. Some of the early results and possible scenarios will be presented at the PAC Meeting in November.

The main features of the proposed future R&D program would be:

a) Development of optimized emulsion in close collaboration with photographic emulsion vendors,

b) Development of module mass production techniques,

c) Development of automatic scanning and pattern recognition,

d) Detector parameter optimization for both ν_μ and ν_e final states,

e) Engineering design of the overall emulsion detector, including its support structure.

Recent experiments using emulsion for detection of neutrino interactions are CHORUS (the short baseline $\nu_\mu \rightarrow \nu_\tau$ search) at CERN and the DONUT experiment (direct observation of ν_τ) at Fermilab. Several members of the DONUT experiment are actively working on the proposal for the MINOS HED and others (possibly including some members of the Nagoya group) would become involved if this R&D proposal is approved. The experience gained from the DONUT experiment in detecting both ν_τ's and ν_e's is extremely useful in designing the next generation of emulsion neutrino detectors.

The Nagoya group is particularly interested in optimizing the ECC-type emulsion detector for electron measurements. This capability is an important component of possible experiments to detect $\nu_\mu \rightarrow \nu_\tau$, in both the $\tau \rightarrow e$ and $\tau \rightarrow \rho$ channels, as well as for a $\nu_\mu \rightarrow \nu_e$ experiment. To this end they have started a detailed study of electron response in emulsions, using both simulations and test beam data.

During the past several years the Nagoya group has also worked closely with the Fuji Company to develop the "next generation" of high quality emulsion films which can be mass produced at low cost. This is an essential component in the design of the large mass detectors required for long baseline experiments. The Nagoya group believes that all major issues in the area of production and development have been addressed and more detailed detector design work can proceed soon.

Several members of the MINOS HED group have been independently discussing similar emulsion production issues with the Ilford Company in the UK. A PIPSS grant to Ilford and MINOS collaborators at University College London was recently approved by the UK PPARC funding agency to fund emulsion development work for a MINOS HED, including support for UCL Research Associate. Encouraged by this, Ilford has set up a team of 12 people to develop products specifically for a MINOS HED, in close collaboration with MINOS experimenters.

Another potential supplier of nuclear emulsions is FOMOS in Moscow. We have initiated interactions with that factory and they have expressed strong interest in working with us to produce a product optimized for our application. Our collaborators at ITEP, Moscow have already received and tested a number of FOMOS emulsion samples produced under different conditions.

Our proposed strategy emphasizes an early start with an emulsion detector that could make a significant contribution to the search for $\nu_\mu \rightarrow \nu_e$ oscillations, perhaps occurring in the presence of a significant rate of $\nu_\mu \rightarrow \nu_\tau$ oscillation events. The further evolution of the emulsion program would be determined later, depending on how physics evolves and on what we learn in the first stage of our program.