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A NEW LONG BASELINE NEUTRINO OSCILLATION EXPERIMENT AT BROOKHAVEN

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Abstract

A new proposal for a long baseline neutrino oscillation experiment has recently been put forward at Brookhaven. The experiment is motivated in part by the observation of an apparent deficit of muon neutrinos from interactions in the atmosphere. Both the neutrino beam and the detectors are being designed to maximize the probability of observing a positive signal, if one is present.

1 Introduction

On Feb. 22, 1994, the Government of Canada announced it would not participate in the construction of the KAON Factory at TRIUMF. One of the potential flagship experiments at KAON would have been a long baseline neutrino oscillation experiment which could have covered about ten square orders of magnitude of unexplored vacuum oscillation space, and therefore had an enormous discovery potential. It is likely that such a measurement could have reached a limit in mass-squared difference of about 10^{-4} eV^2, close to the solar neutrino level! The interest in this experiment at TRIUMF, and for neutrino experiments in general, led to the formation of a working group which held regular meetings and organized several workshops to elucidate the physics and to begin to understand the problems that would have to be solved before a neutrino facility became a reality at KAON. In fact, all the wonderful neutrino physics that could have been done at KAON was outlined three years ago at this Institute,[1] see also.[2] Therefore, when the idea for a proposal[3] for a long baseline oscillation experiment was put forward at Brookhaven, it was natural that TRIUMF physicists should become involved since, besides the common physics interest, many of the same problems already addressed at KAON would have to be faced at Brookhaven as well. For example, the addition of the Front End Booster to the AGS means that there will now be 6×10^{13} protons per macropulse, about four times as many as previously and the same as at KAON. The shock created by this intense pulse of protons bombarding the production target could well lead to the target's destruction unless great care is taken in its design. It might be mentioned that the KAON target would have faced the additional difficulty that the pulses would have come fifteen times more often!

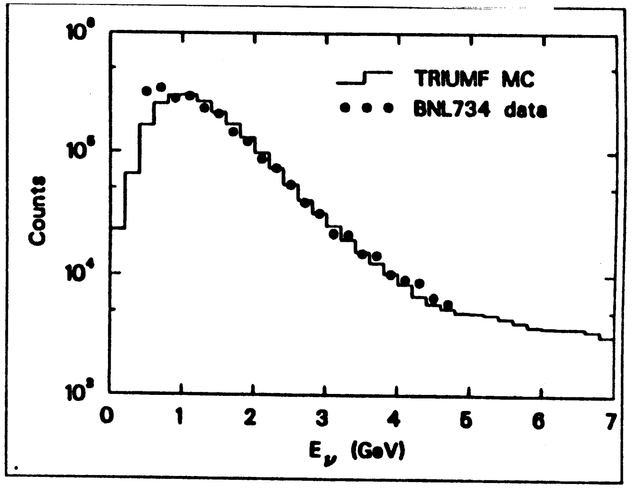

Figure 1: Comparison of the muon neutrino beam spectrum measured in Brookhaven E734[5] with a parameter free calculation using the TRIUMF Monte Carlo code.

It was already known by the proponents of the Brookhaven experiment that some expertise had been developed at TRIUMF in regards to some of these challenging technical issues. It was not known that a new beam simulation code had been developed by the working group. This GEANT based program was originally a copy of a new code developed by the CHORUS collaboration at CERN, but already it has evolved into what could truly be called a TRIUMF program.[4] Shown in Fig. 1 is a comparison of the neutrino energy distribution measured in Brookhaven experiment E734[5] with a parameter free Monte Carlo simulation using this new code.

It was the impressive ability to simulate this data that has given the new collaboration great confidence that many of the limiting systematic effects in previous experiments can be better understood. It has also led to a novel way of improving the lower limit of mass difference that can be explored. The technique will be explained shortly during the discussion of the neutrino beam.

The members of the working group are listed in Table 1; without their contribution during the days when KAON looked possible it is unlikely that TRIUMF physicists would be involved in the present proposal.

The motivation for the experiment is discussed in the next section. In the section following, it will be shown how great care is being taken in the design of the experiment so that if a signal is present it will not be missed, and if one is indeed

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Table 1: Members of the TRIUMF Neutrino Working Group.

seen, there will be no ambiguities in its interpretation.

2 Motivation

There has already been much discussion this week of the cosmological interest in learning whether or not neutrinos have any mass, and whether or not there is mixing among the generations in the same way as in the quark sector. Of course, these questions are also among the outstanding issues yet to be resolved in the Standard Model. Therefore, nothing more will be said about these aspects of the motivation for the experiment, except to stress that theory is of no help in trying to decide where to look for neutrino masses and mixings. For example, see-saw mechanisms, both quadratic and linear, have been mentioned by previous speakers, but even here it isn't clear whether the Dirac mass should be proportional to the quark or the charged lepton masses, and what the scale should be for the unification mass. In short, theory can be made to predict just about any mass!

Therefore it is important that the immediate motivation for this proposal is a hint of a possible neutrino mass from an experimental observation; namely, the so-called atmospheric neutrino anomaly.[6,7] Briefly, cosmic rays interacting with nuclei in the upper atmosphere produce various mesons, but mostly pions, and these decay into muons and muon neutrinos. The muons, in turn, decay into electrons, electron neutrinos and muon neutrinos (it is not necessary here to distinguish between neutrino and anti-neutrino). Adding up the muon-like neutrinos and the electron-like neutrinos, it can be seen that they would be expected to be in the ratio of 2:1. Of course there are many complicating factors such as other mesons being produced and subsequently decaying, and a dependence on energy and so on, but the fact is

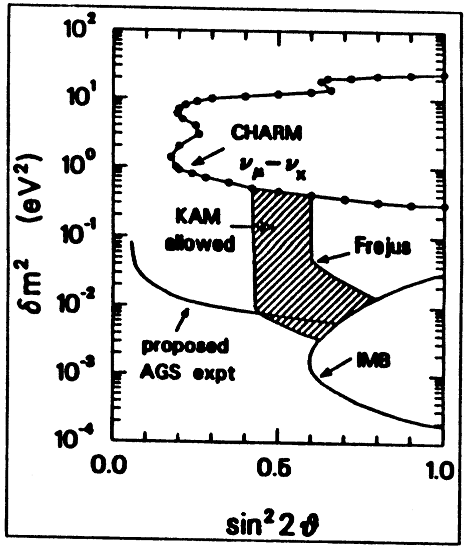

Figure 2: Limits reached in previous oscillation experiments. The hatched area shows the region allowed by the atmospheric neutrino measurements. A positive signal could be identified in the present experiment in the region above and to the right of the line marked "proposed AGS expt" in about 3 months of data taking.

that the ratio that is observed is several standard deviations less than the expected ratio, as measured by Kamiokande[6] and IMB.[7]

This observation has been interpreted in terms of neutrino oscillations resulting from a finite neutrino mass. Recall that the probability that a given flavour of neutrino will evolve into a different flavour is given by

$$P(\nu_\mu \rightarrow \nu_x) = sin^2(2\theta) sin^2(1.27 \delta m^2 L/E_\nu) \tag{1}$$

where $\delta m^2 = m_1^2 - m_2^2$, where m_1 and m_2 are the two mass states mixing together,
L is the baseline for the measurement,
and E_ν is the neutrino energy.

The atmospheric measurements lead to an allowed region in vacuum oscillation space as shown in Fig. 2. The intent of the experiment at Brookhaven is to explore this same region, but with an accelerator produced neutrino beam. In passing, it might be remarked that the "baseline" for the atmospheric measurements is from

10-100 km for the downward going sample, and the neutrino energy range is from 0.3-1.5 GeV. For this experiment the baseline will be 24 km and the energy range 0.5-2.0 GeV, so it nicely mimics the atmospheric measurements and truly will test the interpretation of that result.

3 The BNL Experiment

In general, there are two types of oscillation experiment. In an appearance experiment, the beam is examined for the presence of a flavour of neutrino not present in the original beam. The advantage of this type of measurement is that although the signal will be small, it is characteristic. On the other hand, a disadvantage is that if there is an oscillation, but it is with a sterile species - one that does not interact in the detector - then the signal will be missed. In a disappearance experiment, a greater than expected loss of flux with distance is looked for. This overcomes the objection above; oscillation with any flavour will give a signal. However, the method relies on the subtraction of two large numbers so there is a larger statistical uncertainty.

One of the features of the present experiment is that it is a combination of both types of measurement. The primary goal is to search for an unexpected loss of muon neutrino flux at a detector (D24) located 24 km from the source. A secondary, but potentially very important, signal, can be provided by the appearance of electron neutrinos in this far detector. Since there is only about a 1% ν_e contamination in the original beam, if as few as 10% of the initial muon neutrinos oscillate into electron neutrinos there would be an order of magnitude increase in the number of ν_es observed in D24 over the number expected. In addition, the detectors are sensitive to neutral current (NC) events, which are flavour blind. Therefore another very important signal will be provided by the ratio of neutral current to charged current (CC) events in each detector. Any changes in this ratio with distance will be another indication that oscillations are occurring. It should also be noted here that the ratio is essentially independent of the beam intensity, so a systematic error in determining the flux will not affect a conclusion about oscillations.

3.1 *Neutrino beam*

There are several advantages in using an accelerator to produce the neutrinos, rather than just taking them as they come from the atmosphere. First, the composition, flux and spectrum of the beam can be measured near the source before oscillations have occurred. Differences in these parameters can then be looked for some distance from the source. On the other hand, it is difficult to imagine a practical, direct way to measure the initial atmospheric "beam". Moreover, the accelerator produced beam comes from a known direction at a known time, so it is possible to discriminate against backgrounds. Furthermore, the experiment can be designed so that there will be a good statistical sample. The interpretation of the atmospheric anomaly is based on only a few hundred events, perhaps there are a thousand or so by now, accumulated after several years of collecting data. The present experiment will detect this many events in about a month! Finally, with an accelerator produced beam, the energy spectrum can be tuned to maximize the likelihood of observing an oscillation signal.

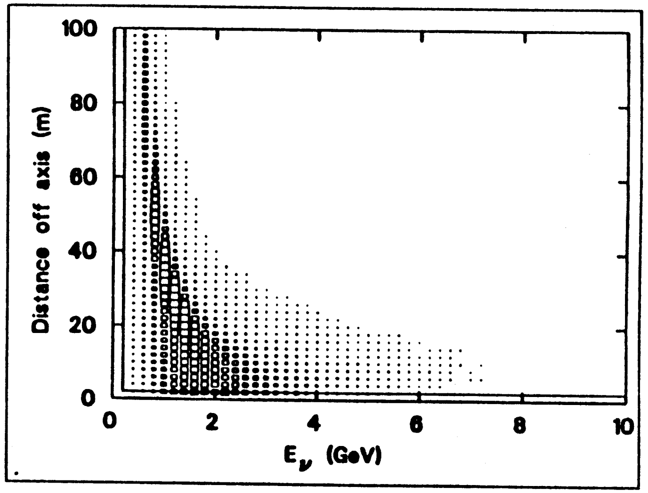

Figure 3: Scatterplot showing how, at 1 km from the source, the spectrum softens as the distance off axis is increased.

The means by which this adjustment can be made is illustrated in Fig. 3 and Fig. 4. First, it can be seen from equation 1 that the smallest values of δm^2 are reached for the lowest neutrino energies. The scatterplot in Fig. 3 shows how for detector D1, located 1 km from the source, the spectrum can indeed be softened by increasing the distance that the detector is positioned from the beam axis. This is further illustrated in Fig. 4 in which slices of Fig. 3 are taken in one degree steps. The arrows along the abscissae mark the positions of the peaks, and these show that the peak energy shifts from about 1.3 GeV for the on-axis spectrum to 0.5 GeV for the spectrum 3 degrees off-axis. In Fig. 5, the zero degree spectra are overlaid with the 1.5 degree off-axis spectra for detectors located 1, 3 and 24 km from the source. This figure is a dramatic illustration of how the beam has been shaped for the specific purposes of this experiment. The spectra peaks are clearly shifted to lower energies in the off-axis spectra, and in addition there is more flux at

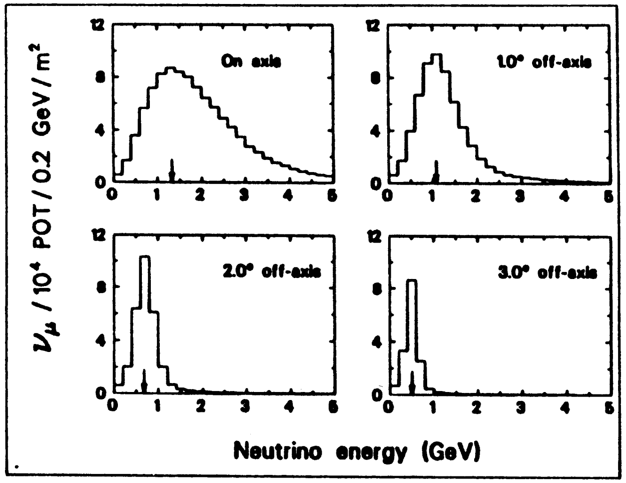

Figure 4: Four positions for D1 illustrating how the spectra soften as the detector is moved off axis. The arrows mark the approximate peaks of the spectra.

these important lower energies. Furthermore, the suppression observed for the high energy parts of the spectra is also desirable; there will then be a relatively lower chance for a high energy event to appear in the low energy part of the spectrum through some of its energy not being deposited in the detector. These misidentified high energy events could otherwise wash out an oscillation signal. It is likely that the detectors will be placed close to this angle (1.5 degrees) off-axis; it can be seen in Fig. 4 that although the peak energy is even lower at 3 degrees, by this angle the flux is beginning to decrease significantly.

The idea of going off-axis to soften the neutrino energy spectrum is hereby claimed for the TRIUMF Neutrino Working Group. Again, without their interest in KAON neutrino physics, the simulation program that allowed this observation to be made would not have been developed at TRIUMF.

3.2 *Detectors*

Successful detection of all the various types of events requires that the detectors have several crucial properties. First, because neutrino cross sections are so small, the detectors must have a large mass. Nevertheless, in order to take full advantage of the $1/E_\nu^2$ factor in the oscillation probability (see equation 1) they must have good energy resolution and therefore must be fully active. In addition, to make

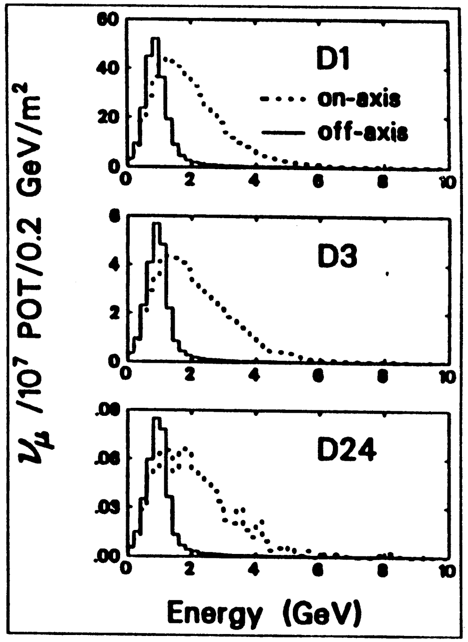

Figure 5: Comparison of the on-, and 1.5 degree off-, axis spectra at the three detector locations.

use of the pulse time structure of the beam for cosmic ray rejection, they must also exhibit good time resolution. Finally, it will be necessary to distinguish muon events from electron events, and therefore there must be good particle identification characteristics. Imaging water Cerenkov detectors meet all of these requirements; furthermore, they are a well known technology as demonstrated by Kamiokande and IMB.

It was originally planned to place two smaller detectors up close to the decay tunnel, at approximately 1 km and 3 km distance, and a larger detector at the far location. The purpose of the first two detectors is to allow a separation to be made between the measurement of the neutrino beam properties and the detector response. The larger size of the far detector would make up for the loss of solid angle. However, it is important to remember here that the atmospheric neutrino results suggest a range of mass and mixing angle where there might well be a positive signal. Therefore, it is now believed that it would be a mistake not to use identical detectors at all three locations, because a different sized detector would introduce new systematic uncertainties which could complicate interpretation of the results. Further, it will be shown in the next section that the use of identical detectors makes possible a variety of consistency checks that reduces the chance of undetected systematic errors. As a result, it is now planned to place two detectors, each identical to the close detectors, at the far location. The two together have almost the same mass as that originally envisaged for the one larger detector.

The final size of the detectors has not been settled, but they will be about the same size as that of the Kamiokande detector - cylinders 16m in diameter and 16m high. They will each contain about 3 kilotons of water and will be viewed by 1900 20cm diameter photomultiplier tubes.

3.3 *Analysis of the data*

The primary signal for the disappearance experiment is the CC quasielastic scattering of a muon neutrino off a neutron, $\nu_\mu n \rightarrow \mu^- p$. Backgrounds arise from cosmic ray muons entering the detector, and from both CC and NC single and multiple pion production reactions on nucleons. As already mentioned, the cosmic muons can be discriminated against by taking advantage of both the time structure and direction of the beam. The pion production reactions should occur at less than 25% of the rate of the primary signal, based on the experience at Kamiodande. In addition, because the detectors are all the same size, these reactions should occur in each detector in the same ratio to the quasielastic events, so it will be possible to correct for them reliably. In short, there should be no serious background. The fact that the ratio of pion reactions to quasielastic reactions should be the same in all four detectors also provides one of the consistency checks mentioned in the previous section.

Another check on systematic uncertainties will be achieved by analyzing separately the contained and exiting events. Again, because the detectors are identical, the ratio of these events should be the same in all detectors. Furthermore, separate analysis of these two event types provides a check of the Monte Carlo simulation of the detector response, which should not only successfully predict the ratio, but also the vertex, momentum and angle distributions of each type.

The good particle identification characteristics of these detectors makes it possible to separately identify electron neutrino and muon neutrino induced events, and so identify the appearance channel mentioned previously. Further to that discussion, if there is a reduction of ν_μs and no corresponding increase in ν_es, then the oscillation must be into some other channel, either to ν_τ or to a sterile species, ν_s. The detectors' sensitivity to the flavour blind NC production of π^os then makes it possible to decide between these two options. There should be a reduction in the number of NC reactions only if there is an oscillation into a sterile channel.

A summary of the various appearance channels is given in Table 2. The second line shows the number of each type of event expected in D24 in the absence of oscillations. The next three lines show how the number of events would vary assuming oscillations into each specific channel. Since the three signal channels respond differently to each of the three oscillation possibilities, if a signal is seen in the disappearance channel it will be possible, given a large enough signal and adequate statistics, to identify the channel into which the oscillation has occurred. The number of events is based on only 90 days of data taking, so it can be seen that in the fullness of time a good statistical sample will be obtained.

		signal channels		
		$\nu_\mu n \rightarrow \mu^- p$	$\nu_e n \rightarrow e^- p$	$\nu N \rightarrow \nu N \pi^o$
number of events in D24 (assuming no oscillations)		18000	180	3700
oscillation channels	$\nu_\mu \rightarrow \nu_e$	⇓	⇑	=
	$\nu_\mu \rightarrow \nu_s$	⇓	=	⇓
	$\nu_\mu \rightarrow \nu_\tau$	⇓	=	=

Table 2: Expected changes in the yields of the signal channels assuming the various oscillation channels.

Finally, because there are such good controls on systematic errors, it will be very difficult for a spurious signal to appear in the ratio of NC to CC events. Since, as remarked earlier, this ratio is also independent of the beam normalization, a signal in this channel would be a strong indication that oscillations are occurring.

One other check can be mentioned that will be especially important in the event an oscillation signal is seen, and that is that the variation between the expected and observed flux at D24 must be consistent with the variation observed at the distance of the intermediate detector, D3.

4 Conclusions

This experiment is largely motivated by a hint from another measurement that neutrinos may indeed be massive particles. There is then a good prospect for a definitive result of fundamental importance. Besides the primary ν_μ disappearance channel, there is a ν_e appearance channel from which it can be directly inferred whether $\nu_\mu \rightarrow \nu_e$ oscillations are occurring. There is also a neutral current channel from which it can be indirectly inferred whether an oscillation signal in the disappearance channel is due to $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_s$ oscillations.

The experiment exploits the relatively high intensity and low energy of the AGS neutrino beam, and there is no untested new technology. Both the beam and the detectors have been used in previous long duration, successful experiments. Great care is being taken to maximize the probability of observing unambiguously a positive signal, if present. The statistical uncertainties will be small, and the systematic uncertainties will be not only small, but verifiable through a variety of consistency checks made possible by the use of identical detectors at all three locations.

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