Project Description

1 Introduction

The value of θ_{13}, the last unmeasured mixing angle in the neutrino mixing matrix, is a pivotal question in neutrino physics today. Its order of magnitude points the direction for both theory and experiment as we begin to explore the implications of neutrino oscillations at a fundamental level. The first step is an experiment that can quickly and inexpensively answer the question: "Is $\sin^2 2\theta_{13} > 1\%$?" because this value turns out to be a natural theoretical and experimental break-point.

This grant request is associated with an international collaboration of neutrino physicists who propose to modify the existing neutrino physics facility at the Chooz Nuclear Power Station in France [1] to perform a two-detector experiment, Double Chooz, which will answer this question. The Double Chooz Experiment, which takes advantage of an existing laboratory and infrastructure, offers the world particle physics community a relatively quick and inexpensive opportunity to measure $\sin^2 2\theta_{13}$. With the proposed detector setup, the sensitivity as a function of running time is illustrated in Fig. 1. For $\Delta m^2 \approx 2.5 \times 10^{-3}\text{eV}^2$, Double Chooz will be sensitive to $\sin^2 2\theta_{13} \sim 0.06$ after 1.5 years of data taking (beginning in 2008) with only the far detector, and to $\sin^2 2\theta_{13} \sim 0.03$ or better after 3 years of operation with two detectors. This sensitivity will cover roughly 85% of the currently allowed region.

Theoretical neutrino oscillation models fall largely into two distinct classes with respect to the magnitude of $\sin^2 2\theta_{13}$. Some models indicate that $\sin^2 2\theta_{13}$ is $O(10\%)$. These are largely grand unified models based on the gauge group SO(10) [2, 3, 4]. On the other hand, models based on flavor symmetries [5] or M-theory [6] favor much smaller values of $\sin^2 2\theta_{13}$ ($O(0.1\%)$). The results of the Double Chooz experiment will indicate which of these two classes of models is viable.

The value of $\sin^2 2\theta_{13}$ also sets the design and price scale for experiments needed to resolve the fundamental question of the mass hierarchy and to search for CP violation. If $\sin^2 2\theta_{13}$ is $O(10\%)$, then the planned Nova [7] and T2K [8] experiments can address these questions [9]. For example, Fig. 2 shows the $\sin^2 2\theta_{13}$ regions where a combination of Nova and T2K can determine the mass hierarchy at the 95% CL; the vertical lines are the Double Chooz sensitivity for 1.5 and 3 years of data. Nova and T2K will only be able to measure the hierarchy if Double Chooz measures a nonzero value for $\sin^2 2\theta_{13}$. On the other hand, if $\sin^2 2\theta_{13} < 1\%$ a Very Long Baseline Experiment will be required [10]. Design decisions on these options are now being made and information on $\sin^2 2\theta_{13}$ is needed quickly.

A reactor-based $\overline{\nu}_e$ disappearance measurement will provide the best measurement of $\sin^2 2\theta_{13}$. The leading-order dependence of the oscillation probability for a reactor experiment, P_R, and a long baseline experiment, P_{LB}, is:

$$P_R = 1 - P(\overline{\nu}_e \to \overline{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2\left(1.27\Delta m^2_{31} L/E\right) + \text{negligible corrections}$$

$$P_{LB} = P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(1.27\Delta m^2_{31} L/E\right) + \\ + \text{significant corrections}(\delta_{CP}, sign(\Delta m^2_{13})),$$

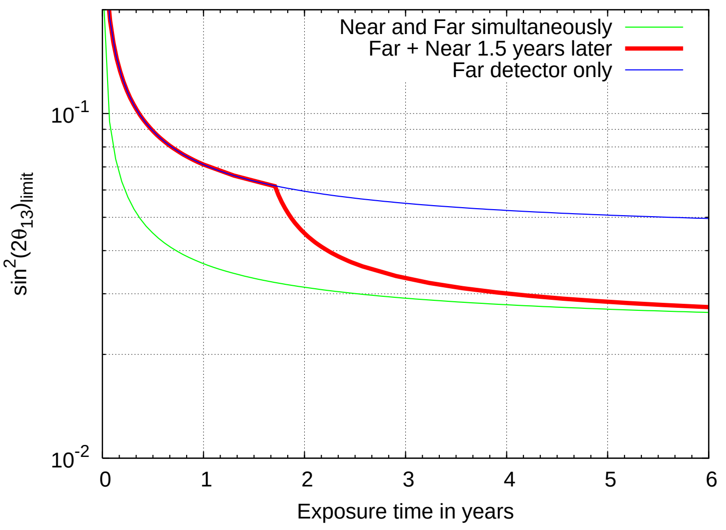

Figure 1: $\sin^2 2\theta_{13}$ *sensitivity as a function of time for the current detector installation scenario.*

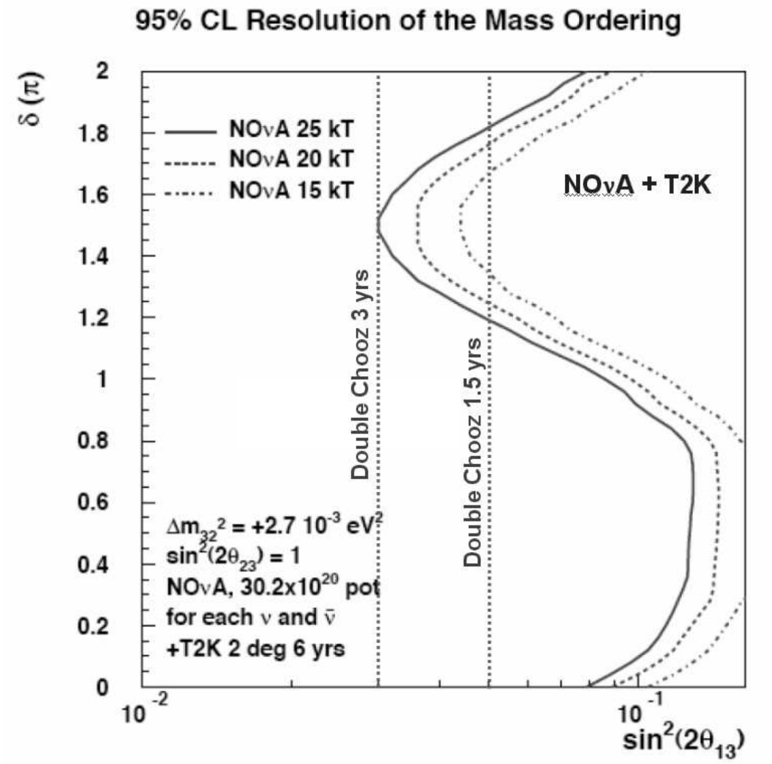

Figure 2: Regions in the δ_{CP} *versus* $\sin^2 2\theta_{13}$ *plane where a combination of Nova and T2K can determine the mass hierarchy (sign of* Δm^2_{13}*). The vertical lines correspond to the Double Chooz 90% CL sensitivities for 1.5 and 3 years of data. (Nova and T2K results from G. Feldman's talk at the HEPAP University Subpanel meeting on Sept. 8, 2006)*

where $\theta_{13}, \theta_{12}, \theta_{23}$, Δm^2_{12}, Δm^2_{23}, are the six oscillation parameters, and δ is the CP violating phase. The higher-order corrections for the reactor probability are quite small, allowing a measurement of $\sin^2 2\theta_{13}$ that is free of ambiguities and degeneracies. On the other hand, the full expression for the long-baseline probability introduces many degeneracies and correlations between the physics parameters θ_{23} and δ_{CP}, plus the mass hierarchy through matter effects even before experimental uncertainties are taken into account [11]. Therefore, a measurement of P_{LB} corresponds to sizable regions in the physics parameter space.

The Double Chooz experiment is being mounted by a collaboration of physicists from France, Spain, Germany, UK, Japan, Russia, and the U.S. In the U.S., both NSF and DOE supported groups are working on the experiment. The NSF groups (University of Chicago, Columbia University, and Barnard College) are submitting this collaborative proposal to request support for a three-year project to design, construct, and install an outer muon tracking and tagging system for both the near and far detectors. This system is a key component of the experiment and will allow these groups to take a significant role in the full project. Supplemental R&D funds were awarded to this group in the summer of 2006 to initiate and expedite the initial phases of the outer muon project. With the funding described in this proposal, the outer muon system can be installed at the far detector site in the summer of 2008 and at the near detector site in the fall of 2009.

The DOE supported groups are also taking a strong role in the experiment. Those groups have worked on designing the analog electronics, calibration, and monitoring systems for Double Chooz and are now requesting DOE support to fund the construction of those systems (See “Proposal to participate in the first measurement of θ_{13}: The Double Chooz Experiment” submitted to the DOE[12].) The combination of systems being proposed by the NSF and DOE groups represent a coherent U.S. program to understand and reduce backgrounds and systematic errors that will be critical for the success of the Double Chooz experiment.

2 The Double Chooz Experiment

The Double Chooz experiment will be performed at the Chooz Nuclear Power Station, the site of the original Chooz experiment (see Fig. 3). The facility has two 4.27 $\mathrm{GW}_{thermal}$ reactors separated by 140 m. The experiment will use two almost identical detectors – a “near” detector at an average distance of 280 m from the two reactor cores and a “far” detector at an average distance of 1050 m. The far detector will use the cavern with 300 m.w.e. shielding excavated for the original Chooz experiment (see Fig. 4); the near detector will be placed in a new hall constructed at a distance of 280 m from the reactor cores with an overburden of 30 m of rock (85 m.w.e.).

Compared to original CHOOZ experiment, which used a single detector, the use of two detectors eliminates sensitivity to calculations of reactor flux, and only requires a knowledge of the relative acceptance of the two detectors rather than absolute acceptance. The cancellation of these important systematic errors will allow measurements of $\sin^2 2\theta_{13}$ almost an order-of-magnitude better than the previous best measurement from the original Chooz experiment [13]. The improved detector design will also make the acceptance easier to understand, and will reduce and make better measurements of backgrounds.

Antineutrinos will be detected through the inverse beta decay (IBD) reaction: $\overline{\nu}_e + p \rightarrow e^+ + n$. The $\overline{\nu}_e$ target in each detector consists of approximately 8.8 tonnes of liquid scintillator loaded with 0.1% Gd. Antineutrino events will be identified by a coincidence between the prompt positron signal, which provides a direct measure of the neutrino energy, and the delayed signal from neutron capture on Gd. The neutron capture on Gd results in about 8 MeV of energy in ~ 5 photons. The capture time is about 30 μs, which is almost an order of magnitude shorter than the capture time on hydrogen. About 85% of the neutrons capture on Gd.

Figure 3: Overview of the Double Chooz experiment site. The insets show the near detector hall (near the center of the photo) and the far hall (at the right edge of the photo.)

2.1 Double Chooz Detector Design

Table 2.1 summarizes parameters of the Double Chooz experiment. Each detector consists of a series of concentric cylinders, as shown in Fig. 5. Starting from the center of the target, the detector elements are:

Target The target vessel is an acrylic cylinder 246 cm high and 230 cm in diameter; the acrylic walls are 1.2 cm thick. It contains 10.3 m^3 of liquid scintillator loaded with 0.1% Gd. Thus, the target mass for the measurement is about 8.8 tonnes.

Gamma Catcher The next liquid volume is the γ-catcher, a 55-cm-thick buffer of nonloaded liquid scintillator (22.6 m^3) with the same optical properties (light yield, attenuation length) as the target volume. This scintillating buffer increases the efficiency for detecting the photons from the neutron capture on Gd and from the positron annihilation.

Nonscintillating buffer A 105-cm-thick region of nonscintillating liquid (114.2 m^3) surrounds the Gamma Catcher and serves to decrease the level of accidental background (mainly the

Figure 4: Picture of the Double Chooz far detector site taken in September 2003.

contribution from photomultiplier-tube radioactivity). This buffer will reduce the singles rates in each detector by two orders of magnitude with respect to those in the original CHOOZ experiment, which had no such buffer.

Buffer vessel and PMT support structure This vessel is made of 3-mm-thick stainless steel sheets and stiffeners. A total of 534 phototubes (8 inch) in a uniform array are mounted from the interior surface of the buffer vessel.

Inner veto system Outside of the buffer vessel, an additional 50-cm-thick region is filled with liquid scintillator and instrumented with phototubes. This "inner-veto" detector will be used in combination with outer-veto detector to tag cosmic-ray muons which may produce backgrounds in the target region.

Outer veto system A large coverage muon system is also placed above the detector. This "outer-veto" system, which is the focus of this proposal, will be described in detail in the following section.

2.2 Systematic Uncertainties

With about 45,000 events expected in the far detector over a 3-year run, the statistical uncertainty associated with the near to far comparison is expected to be 0.5%. In order to take advantage of this statistical precision, the experiment needs to reduce the systematic uncertainties to this level. Table 2.2 summarizes conservative estimates of the systematic uncertainties in the relative comparison of the near and far detectors in comparison the the previous CHOOZ single detector measurement. Many of these estimates have been obtained using actual measurements from the CHOOZ experiment and therefore should be more reliable than typical proposal numbers. In

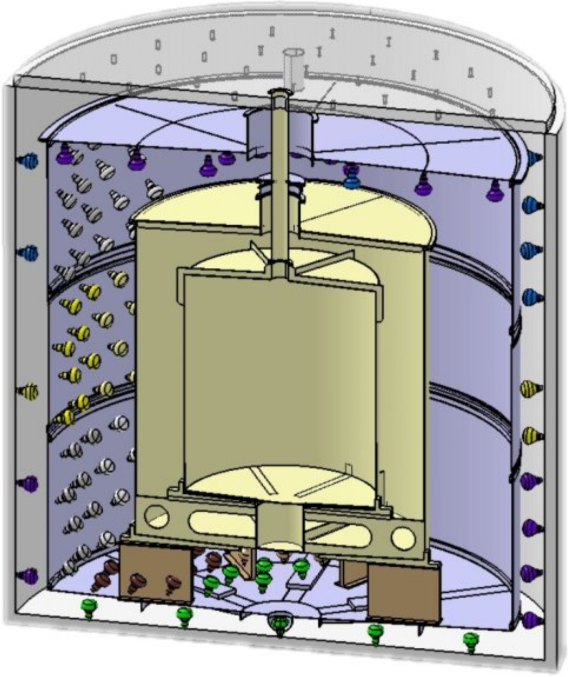

Figure 5: Diagram of Double Chooz Detector. The outer veto is not shown.

Table 1: Key parameters of the proposed Double Chooz experiment.

Parameter	Value	Comment
Thermal power	4.27 GW	each of 2 cores
Electric power	1.5 GWe	each of 2 cores
$\overline{\nu}_e$ target volume	10.3 m^3	Gd loaded LS (0.1%)
γ-catcher thickness	55 cm	Gd-free LS
Buffer thickness	105 cm	nonscintillating organic liquid
Total liquid volume	$\sim$237 m^3	
Number of phototubes per detector	534 8"	13% coverage
Far detector distance	1050 m	averaged
Near detector distance	280 m	averaged
Far detector overburden	300 m.w.e.	hill topology
Near detector overburden	70–80 m.w.e.	shaft
Relative systematic error	0.5%	
Effective bin-to-bin error	1%	background systematics
Running time with far detector only	1–1.5 year	
Running time with far+near detector	3 years	
90% c.l. sensitivity to $\sin^2 2\theta_{13}$	0.02–0.03	(90% CL)

addition, many of the uncertainties associated with efficiencies and cuts may be reduced in the final analysis due to care in making the near and far detector identical in design, materials, and target volumes. The largest uncertainty from the Gd capture percentage can probably be reduced by careful studies of the Gd loaded scintillator properties. In the end, the dominant uncertainty will likely be the relative fiducial volume of the detectors which is assumed to give a 0.2% error and the oscillation measurement is expected to be statistics limited.

Table 2: Total systematic error on the normalization between the detectors

			CHOOZ	Double Chooz
Reactor		Solid Angle	—	0.2%
Detector	H nuclei in Target	Volume	0.3%	0.2%
		Fiducial Volume	0.2%	0
		Density		0.1%
		H/C	0.8%	0
Detector	Electronics	Dead Time	—	0%
Particle Identification	Positron	Escape	0.1%	0
		Capture	0	0
		Identification Cut	0.8%	0.1%
Particle Identification	Neutron	Escape	1.0%	0
		Capture (% Gd)	0.85%	0.3%
		Identification Cut	0.4%	0.1%
Particle Identification	Antineutrino	Time Cut	0.4%	0.1%
		Distance Cut	0.3%	0
		Unicity	0.5%	0
Total			1.5%	0.5%

2.3 Schedule

The Chooz far detector hall is available now and is currently being refurbished and improved with respect to liquid handling and storage. This is an advantage for our outer veto project since prototype detectors can be taken to the Chooz site during the summer of 2007 to make measurements of rates and distributions. In addition, taking advantage of this existing far detector hall will allow the installation of the far detector starting in late 2007. With this schedule, the installation of the far detector is expected to be completed by the summer of 2008 and oscillation data with one detector can commence at that time. An oscillation measurement at the $\sin^2 2\theta_{13} \approx 0.05$ level is expected with about 1.5 years of far-only data.

The new near detector hall is expected to be completed at the end of 2008. At that time, the near detector can be installed and two detector running can start around summer of 2009. The expected sensitivity to $\sin^2 2\theta_{13}$ as a function of time was shown in Fig. 1 and leads to an estimate of a sensitivity at the $\sin^2 2\theta_{13}$ below the 0.03 level in 2012.

3 Backgrounds and the Outer Veto

Understanding and subtracting background events is a key requirement for reactor experiments. The backgrounds that mimic the inverse beta decay signal may be separated into two categories: uncorrelated and correlated. Uncorrelated background events result from random coincidences between two different events, that together mimic the IBD signal. For example, a coincidence between a radioactive decay and a neutron produced by a cosmic ray muon could produce a fake signal event. Fortunately, the level of these events can be measured easily by changing the required time coincidence window (*e.g.* by exchanging the required sequence for the positron-like and neutron-like signals).

Correlated backgrounds, in which both the positron and neutron-like signals result from the same parent particle, are more problematic. Three types of correlated backgrounds are considered:

- *Fast neutron.* Fast neutrons produced by cosmic ray muons can fake the IBD signal by elastically scattering in the Gamma Catcher or target volume and subsequently capturing on Gd. The recoil protons from the elastic scatter can mimic the prompt positron signal from inverse beta decay, followed by the delayed n+Gd capture signal.

- *Muon capture.* Muon capture, particularly on nuclei in dead material along the muon track, can produce fast neutrons that mimic the IBD signal as described above.

- ^{9}*Li.* Spallation from cosmic ray muons can create ^{9}Li inside the detector. About 50% of ^{9}Li β decays produce a neutron that can capture on Gd, which along with the prompt signal from the β mimics the IBD signal. The 178 ms half life makes these events difficult to veto without producing unacceptable dead time.

All of the background sources are associated with cosmic ray muons (even accidental backgrounds usually result from a coincidence between a radioactive decay and a muon-induced neutron). The muon flux at the near detector hall, protected by approximately 70 m.w.e. of rock overburden, is estimated to be 5.9×10^{-4} cm^{-2}s^{-1} with a mean muon energy of 30 GeV; the far detector hall is protected by an average of 300 m.w.e. of rock, resulting in an estimated flux of 6.2×10^{-5} cm^{-2}s^{-1} with a mean muon energy of 61 GeV. These yield raw muon rates at the near (far) site of 5.9 (0.62) Hz per m^2 of veto coverage. However, muons passing through the central target and gamma catcher deposit orders of magnitude more energy than IBD events and are easily identified. Most of the muons passing only through the mineral oil buffer will also produce significant Cerenkov light, and, thus, be identified and rejected.

Table 3 summarizes the expected background levels in the near and far detectors after eliminating muons passing through the central detector. (Central detector muons have not been eliminated from the muon capture rates.) The total background rates in the near and far detectors are estimated to be 306 and 33 events/day, respectively. These rates result mainly from muon capture, against which the combined veto detectors should have excellent efficiency, as discussed below. Even rejecting muons which have been tagged in the central detector, these are unacceptably high, because many background events are produced by muons that pass some distance away from the central detector.

The Double Chooz experiment uses a two-part veto system to detect these “near-miss” muons: the inner veto, a 50 cm thick liquid scintillator detector that surrounds the three central detector

Table 3: Background rates at the near and far detectors after eliminating muons hitting the central detector, but without using the inner or outer veto systems. (Central detector muons have not been eliminated from the muon capture rates.) Accidentals involving radioactive decays in the PMT glass and other detector material are shown separately.

Detector	Site		Background				
			Accidental			Correlated	
			Materials	PMTs	Fast n	μ-Capture	^{9}Li
Double Chooz		Rate (d^{-1})	0.5 ± 0.3	1.5 ± 0.8	2.0 ± 2.0	28	1.0 ± 0.5
(69 ν/d)	Far	bkg/ν	0.7%	2.2%	2.9%	40%	1.4%
Double Chooz		Rate (d^{-1})	5 ± 3	17 ± 9	9.1 ± 9.1	266	9 ± 5
(1012 ν/d)	Near	bkg/ν	0.5%	1.7%	0.8%	26%	0.9%

volumes (see Fig. 5), and the outer veto, a large-area muon detector placed above the central detector which is the subject of this proposal.

The outer veto is intended both to reduce backgrounds associated with cosmic ray muons and to be a powerful tool in understanding the different background components and the performance of other elements of the Double Chooz detector. Its functions include:

- Reducing the fast neutron background at the near (far) detector by a factor of 5 (2) beyond what can be achieved with the inner veto alone.
- Measuring the efficiency of the inner veto.
- Selecting samples of cosmic muons hitting rock, steel shielding, support structures, etc. to study neutron backgrounds originating from these uninstrumented regions.
- Providing a tracked sample of muons to study ^{9}Li background.
- Providing redundancy for the inner veto. For example, the outer veto will detect muons traveling down large vertical cable tubes in inner veto volume.
- Eliminating muon capture backgrounds in the steel shielding.
- Reducing accidental backgrounds associated with muons.

To perform these functions, the outer veto must tag muons with a high efficiency over the entire veto volume as well as provide tracking information for muons that pass in and around the central detector.

We have studied the benefit of different levels of coverage for the outer veto system. An ideal system would cover all sides of the detector and would surround significant additional passive shielding. Such a system would either veto muons producing neutron backgrounds, or provide enough shielding to attenuate neutrons produced by muons that did not hit the veto. In combination with the inner veto system, a large "umbrella-style" outer veto situated above the detector will provide much of this function at a significantly lower cost. A top-only design is also the only possibility for the existing far laboratory.

Figure 6 shows, for the near site, the reduction in the fast neutron rate into the Gamma Catcher and target regions as a function of the size of a square outer veto placed 1.1 m above the central detector. This study takes the proper surface distribution of cosmic ray muons as its input, and uses FLUKA to track the muons from the surface to the detector depth and produce neutrons. The rates shown are for muons that produce at least one neutron entering the Gamma Catcher volume. Muons passing through the central detector, which may be rejected without the veto systems, have already been excluded.

These curves assume 100% efficiency where coverage exists. The inner veto is expected to be fully efficient whenever the muon path length in scintillator exceeds 4 cm, less than 1/10 of the thickness of the inner veto. The outer veto efficiency, which will be discussed in the following section, should exceed 99%. Based on Fig. 6, the constraints of the detector hall, and dead time considerations we have decided on an outer veto size of 12.8 m $\times$ 12.8 m for the near detector and 6.4 m $\times$ 12.8 m for the far detector; the details of the outer veto design will be described Section 4.

At the near site, the muon rate hitting the outer veto system will be about 1 kHz, resulting in a 25% deadtime for a 250 μs veto; the muon rate at the far site outer veto will be only $\sim$ 50 Hz, resulting in an order-of-magnitude smaller deadtime. As described in the Double Chooz full proposal [1], these deadtime rates will be monitored and measured using special electronic systems and are expected to only contribute a 0.25% systematic uncertainty in the near to far comparison.

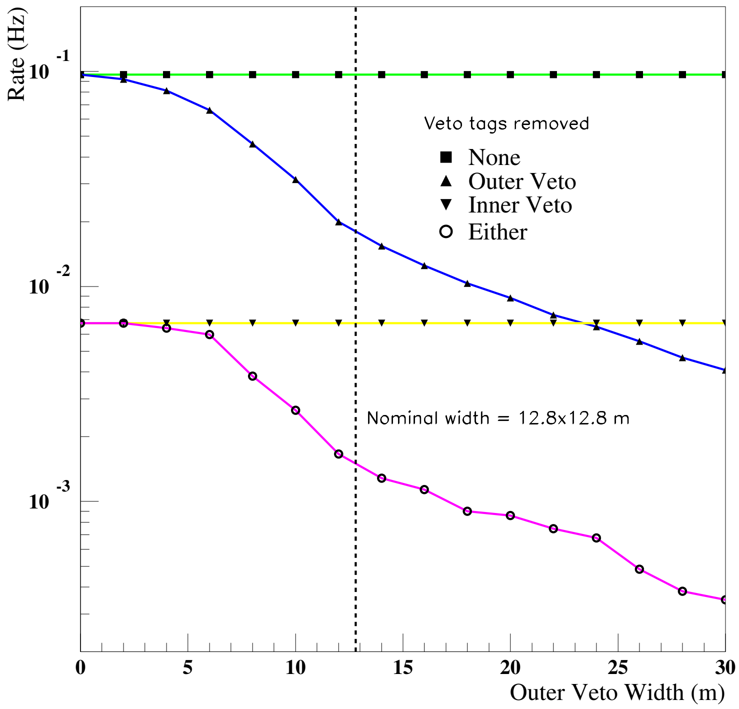

Figure 6: Rate of muon-produced fast neutrons reaching Gamma Catcher volume for top-only veto based on FLUKA.

The Venn diagram in Fig. 7 shows how the inner and outer veto systems complement each other

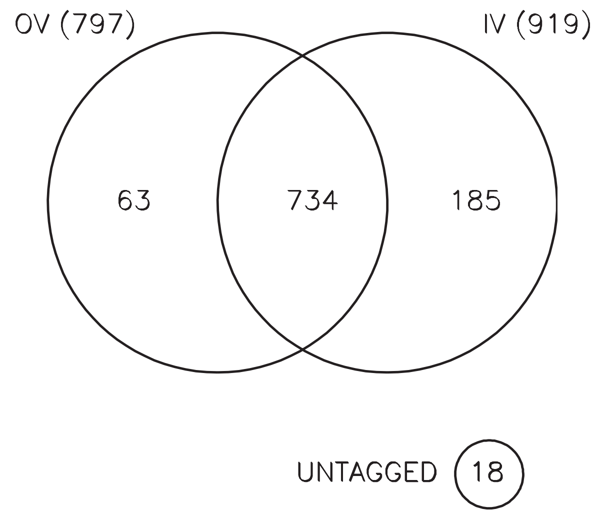

Figure 7: The number of muons (per 1000) producing neutrons which enter the Gamma Catcher and target volumes that are tagged by the inner veto (IV) and outer veto (OV) systems; the number of tags are shown in parentheses. Note that muons passing through the central detector volume are not included, because they can be identified without the veto systems. 18 events are not tagged by either system.

to tag muons that produce neutrons which enter the Gamma Catcher and target regions. At the near site, 80% of these muons which are tagged by the inner veto will also be tagged by the outer veto; 92% of these muons which are tagged by the outer veto will also be tagged by the inner veto. Only 1.8% of muons producing potentially harmful neutrons will be missed by both systems.

Table 4 shows the background levels after rejecting muons crossing the inner veto or outer veto. The total background rate at the near site is 12 events/day (1% of the ν signal); at the far site it is 1.5 events/day (2.1% of the signal). At both sites, ^{9}Li production is expected to be the dominant remaining background.

Compared to the background rates without the veto systems (Table 3), at the near (far) site the accidental rate is reduced by a factor of $\sim$10 ($\sim$5). The fast neutron rate at the near (far) site is reduced by a factor of 60 (20). The difference between the near and far site reduction factors results solely from the reduced outer veto coverage at the far site, which is dictated by the size of the already existing far detector laboratory.

The muon capture rate at both sites is reduced by a factor of $\sim$600. As 99% of the muon captures that produce a background event occur in the acrylic support structure and mineral oil buffer inside the central detector, the inner veto alone will tag these muons with a high efficiency, making the rate reduction at the near and far sites essentially the same. It should be noted that the outer veto will also have excellent efficiency to tag these stopping muons, providing an important redundancy in the case of dead material in the top of the inner veto. The remaining 1% of muon captures which produce background occur in the steel shield, and are therefore tagged only by the outer veto, removing approximately 1 background event per day.

Table 4 also shows the expected systematic uncertainty for the background. Another key reason for the two veto systems is to assure the level of these systematic uncertainties by providing measurements and tagging for the backgrounds. In particular, the outer veto will allow one to track muons into different regions and assess the level of the various types of backgrounds. For example, although the ^{9}Li background rates will likely not be reduced by the veto systems, we expect the veto systems, and the outer veto especially, to be an important tool in understanding the ^{9}Li background level.

Table 4: Background rates at the near and far detectors after using all detector systems (central detector, inner veto, and outer veto) with 100% efficiency.

Detector	Site		Background				
			Accidental		Correlated		
			Materials	PMTs	Fast n	μ-Capture	^{9}Li
Double Chooz		Rate (d^{-1})	0.1 ± 0.1	0.3 ± 0.2	0.11 ± 0.11	< 0.1	1.0 ± 0.5
(69 ν/d)	Far	bkg/ν	0.1%	0.4%	0.2%	< 0.1%	1.4%
		systematics	<0.1%	<0.1%	0.2%	<0.1%	0.7%
Double Chooz		Rate (d^{-1})	0.5 ± 0.3	1.7 ± 0.9	0.15 ± 0.15	0.4	9 ± 5
(1012 ν/d)	Near	bkg/ν	< 0.1%	0.2%	< 0.1%	< 0.1%	0.9%
		systematics	<0.1%	<0.1%	<0.1%	<0.1%	0.5%

4 Outer Veto Design

As described in the previous section, the outer-veto system will be a large-area muon detector placed above the cylindrical Double-Chooz detectors. The outer veto will be made of 5 cm × 1 cm strips of scintillator formed into 6.4 m × 6.4 m planes. These modules will then be combined to form x and y layers of a supermodule that will cover an area of 6.4 m × 12.8 m (12.8 m × 12.8 m) at the far (near) detector site. The scintillator strips will be coextruded with a TiO_2 reflective coating, similar to those used for the MINOS and OPERA experiments. Each strip will be 6.4 m long, and will have a 1.2 mm wavelength shifting fiber glued into a groove created during the extrusion process. Figure 8 shows a cross section of a strip.

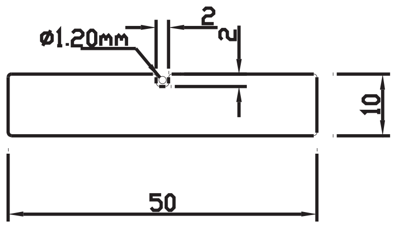

Figure 8: Cross section of scintillator extrusion. The nominal strip length is 6.4 m.

Modules will be built of two 32-strip layers of these strips, with each layer offset by 2.5 cm from the layer below. The resulting modules will be 1.6 m wide. Each 32 strip layer will be separately wrapped in a 0.02" Al skin that provides the light seal and strength for the module. The two 32-strip layers will then be attached to form a 64 strip module (see Fig. 9).

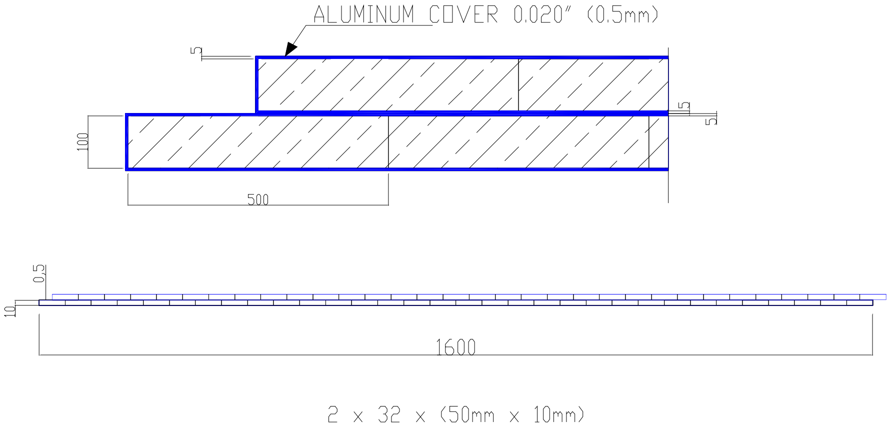

Figure 9: End view of 64-strip module. The detail shows the 0.02"Al skin surrounding each 32-strip layer.

The 64 wavelength shifting fibers on each end will be coupled to a Hamamatsu M64 multianode photomultiplier tubes. Four of these 1.6 m wide modules will be combined to form a single 6.4 m $\times$ 6.4 m plane. Finally, a second 6.4 m square plane rotated by 90 degrees will be added. The resulting 6.4 m square plane with 4 layers of scintillator, shown in Fig. 10, is the basic unit used in the outer veto system.

Based on measurements by the MINOS collaboration, at the midpoint of a strip (i.e., 3.2 m from the end), a muon will result in about 4 photoelectrons. Using this estimate, a requirement of > 2 p.e. in at least one strip in each view will result in an efficiency greater than 99%.

Figures 11 and 12 show the planned outer veto configurations for the near and far detectors. The plans for the near and far detector are different because of the physical constraints of the existing far hall; the near hall will be constructed to accommodate the outer veto design. The near detector will use four 6.4 m square units surrounding the inner detector neck. An additional 6.4 m square unit will be installed above the "glovebox" to provide muon tracking over a limited region. (The glovebox will be used to introduce calibration sources into the central detector.) For the far detector, two of the 6.4 m square units will be installed on either side of the neck along the length of the tunnel. Small additional counters with single-ended readout will be added to cover the resulting gaps next to the neck. Finally, an additional $\sim$ 5m square module will be added above the glove box for tracking; this tracking plane must be smaller because the tunnel roof is arched, reducing the space available above the detector.

4.1 Module Construction

Module construction will be done following procedures developed by the MINOS and OPERA collaborations. We estimate that construction of each 64 strip module will take 3 days using a full-time crew of 2 technicians and 4 undergraduate students.

The main steps in the construction are the following:

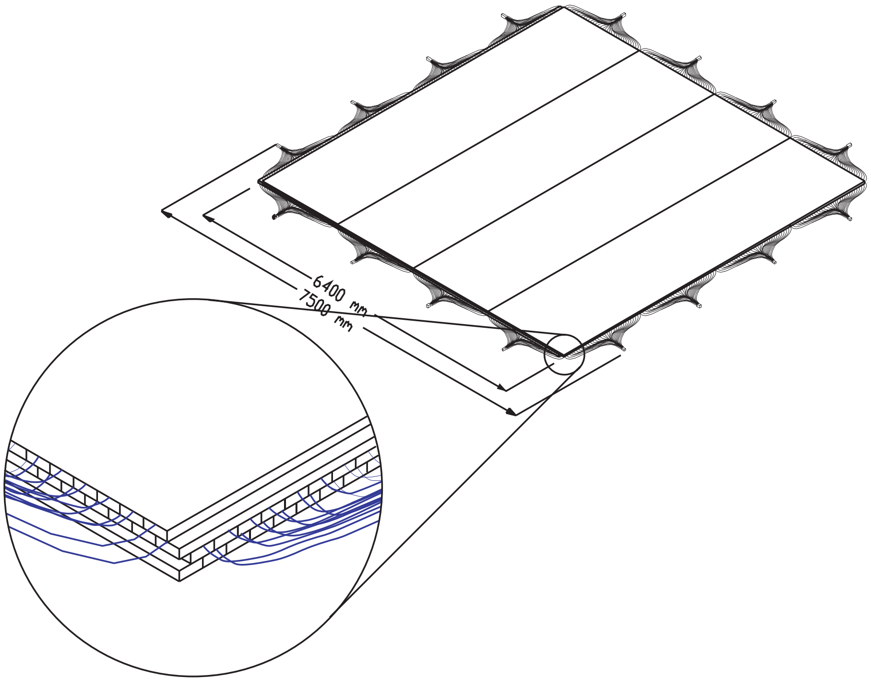

Figure 10: A complete 6.4 m square plane made up of 8 two-layer modules. The inset shows fibers leaving the 4 layers of strips.

- 32 scintillator strips cut to the correct length will be glued into the bottom of an Al skin.
- After curing overnight in a vacuum bag, wavelength shifting fibers will be glued into the scintillator grooves and the fibers routed through plastic guides at the end of the module.
- After the glued fibers have cured overnight, the top of the Al container will be attached either by crimping or with glue.
- Two 32 strip modules made as described above will be glued to each other with a 2.5 cm offset.
- The 64 fibers on each end will be glued into a 64 fiber matrix that matches the M64 pixel layout.
- The fibers will be cut using the diamond-bit fly cutting station. At this stage, the module is ready for mounting M64s to the fiber matrix at each end.

Table 5 summarizes the cost for construction and testing of the scintillator modules; the costs for electronics and installation are given in the following sections. The cost for producing the extruded scintillator is based on a quote from the Fermilab/NIU Extruded Scintillator Facility. It includes all materials and labor. The cost for wavelength shifting fiber is based on a quote from Kuraray.[1] An NSF supplement awarded during the summer of 2006 allowed us to purchase much

[1] Although our nominal design assumes 1.2 mm diameter fibers, we have used the quote for 1.8 mm fiber. As we will be discussed in the section on prototypes, we will investigate whether an unglued 1.8 mm fiber (instead of a glued 1.2 mm fiber) gives sufficient light to ensure good efficiency; if so, the significant simplification in the assembly procedure will warrant the change. We've budgeted for the 1.8mm fiber to allow this possibility.

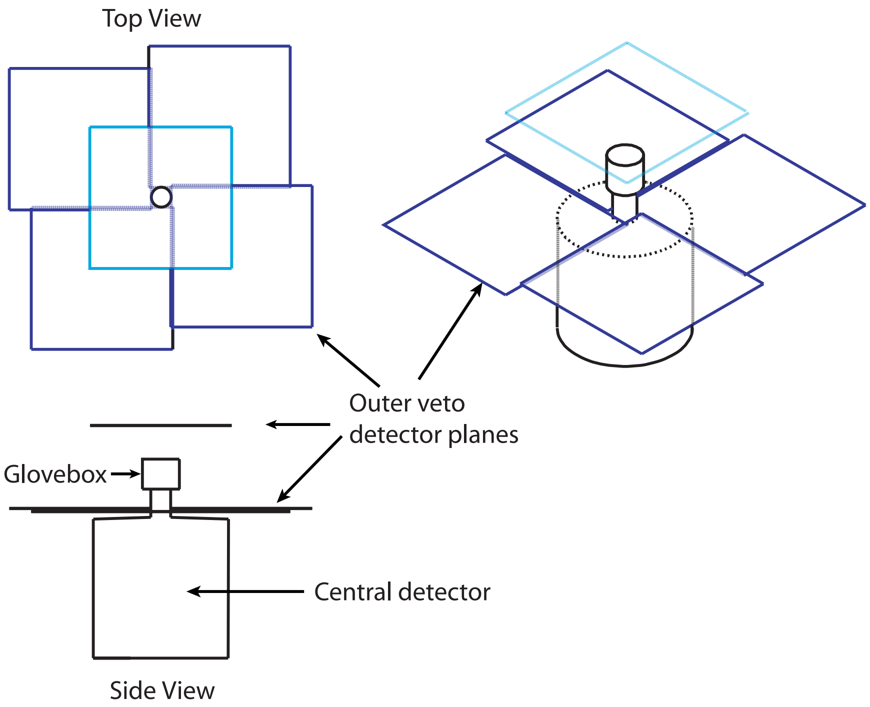

Figure 11: Outer veto layout for near hall. The design includes four 6.4 m square modules placed around the central detector neck, and a fifth 6.4 m square module placed above the "glovebox" to provide limited tracking.

of the infrastructure for module production; this budget includes items not covered by the earlier award. At the site, the 64 strip modules will be attached to an Al support structure on rails; we estimate $12k for each of the eight 6.4m square detector planes. Finally, the budget includes one full year of two technicians and 4 full-time equivalent undergraduates to complete the module assembly.

4.2 Electronics and Data Acquisition

The detector readout will require a total of 128 M64s, 80 at the near site and 48 at the far site. The detector information needed for event reconstruction is the time and location of hits in the veto detector. Some analog information will also be useful to set thresholds.

We have designed a system in which the signals are discriminated and buffered locally to minimize cabling. Figure 13 shows a block diagram of the front-end electronics, which will be mounted on a small card behind each M64. Figure 14 shows the planned arrangement of a card mounted behind an M64. The 64 channels enter a MAROC2 custom integrated circuit, designed at LAL (Orsay) for the ATLAS luminosity monitor. This chip allows adjustment of the electronic gain of each of the 64 channels, which will be needed to correct for the expected factor of 3 pixel-to-pixel gain variation in the M64. The system will also apply three different discriminator thresholds for readout, thus, giving more detailed information for offline analysis. The chip also includes a multiplexed 12-bit ADC path that can be used for calibration, and a direct analog signal path, useful if an external trigger from the muon veto is ever required.

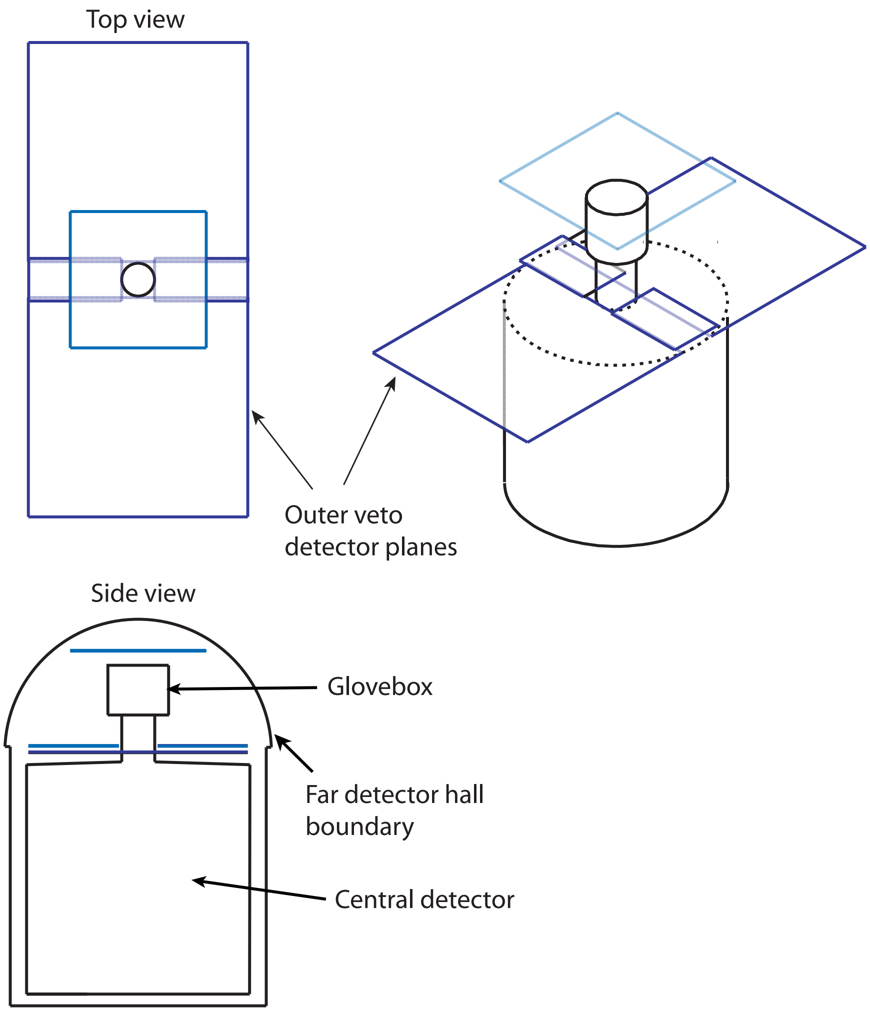

Figure 12: Outer veto layout for far hall. The design includes two 6.4 m square modules placed on either side of the central detector neck, and a fifth smaller module placed above the "glovebox" to provide limited tracking.

The output of the MAROC2 will be fed into an FPGA, also on the board. This FPGA will record the time of hits, buffer the data, provide control signals for the MAROC2, and provide a signal to the central system when data are present to be readout. A parallel to serial converter will be used to transfer data to central receiver boards when the FPGA is polled by the main system.

The system will use the Double Chooz distributed 62.5 MHz clock and time stamps to maintain synchronization with other detector elements. The outer veto data will be read out as a separate data stream of hits and times, and will be merged with the inner detector event records offline. The time offset between the inner and outer detector systems will be measured with cosmic ray muons.

Table 6 summarizes the estimated budget for readout electronics. The M64 price is based on a quote from Hamamatsu. We have included 150 M64s and readout cards providing 22 extra PMT units for spares and testing. For the clock distribution and VME system, we've included the requirements for the near and far readout, one spare component of each type, and also components for a single parallel readout system to be kept operating in the U.S. for tests. For example, the

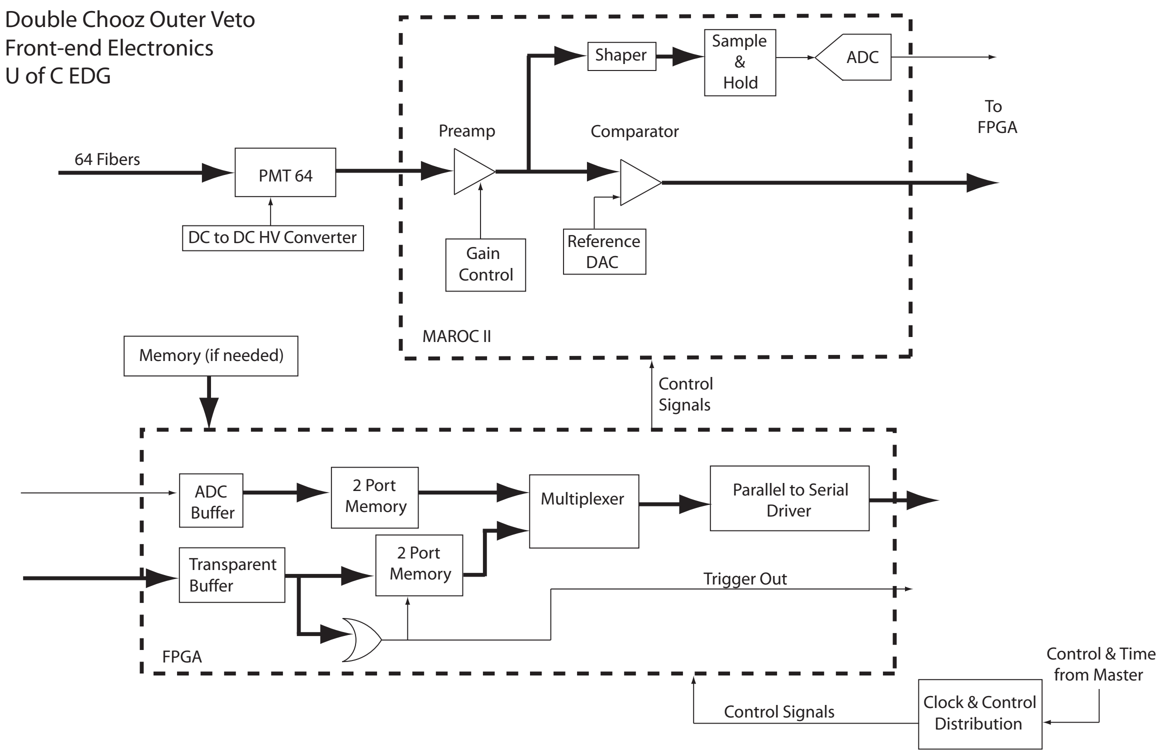

Figure 13: Block diagram for front end readout of outer veto detector.

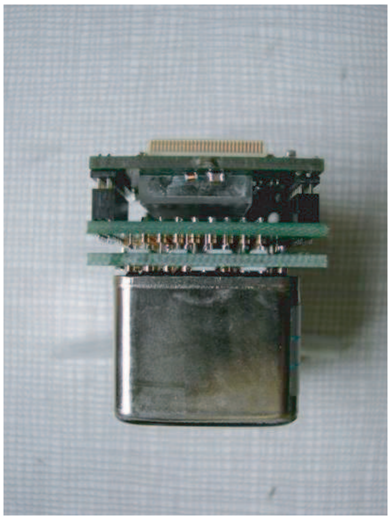

Figure 14: M64 with frontend card.

Table 5: Proposed budget for scintillator module mechanical construction. All personnel costs are fully loaded.

Item	Units	Unit Cost (dollars)	Cost (thousands of dollars)
Coextruded plastic scintillator	26.2 km	-	255
Wavelength shifting fiber	30 km	7.3 / m	220
Additional materials for module assembly	64 modules	2000	128
Module Assembly and Testing Fixtures			
Storage racks	2	5000	10
Scintillator cutting station	1	10000	10
Assembly tables	4	4000	16
Vacuum pumps and bags for gluing	2	5000	10
Support structure with sliding rails			
for 8 module detector planes	8	12,000	96
Mechanical engineering	800 hrs.	60 / hr.	48
Technicians (construction)	4000 hrs.	37 / hr.	148
Undergraduates (construction and testing)	8000 hrs.	13.7 / hr.	109.6
Total			1050.6
30% Contingency			315.2
Total including contingency			1365.8

budget includes 4 VME crates: one for the near site, one for the far site, one spare, and one for a test setup in the U.S. The engineering and technician time are based on our estimates for the design, assembly, and testing of the readout system.

4.2.1 Quality Control

Quality control for different components of this very large system will be critical. Here, we mention only two elements of this testing:

- *M64 testing.*As described in Section 5, a test facility will be built at Barnard College to test and characterize each channel of the 64-channel Hamamatsu H7546 PMTs. The main goal of the test will be to measure the absolute gain of each channel, but several other characteristics such as cross talk and dark current will also be recorded.
- *Complete Module Testing.*We plan to test each completed module with its final electronics on a cosmic ray test stand for 12 hours. This test will allow us to verify the integrity of each module, and will also allow us to make an initial gain adjustment in the MAROC2. Several fixed locations on the modules will also be checked with sources.

Table 6: Proposed budget for readout electronics and DAQ.

Item	Units	Unit Cost (dollars)	Cost in thousands of dollars
Hamamatsu M64s	150	1650	247.5
Frontend:			
Frontend cards	150	32	4.8
MAROC2 ASIC	150	400	60
FPGA	150	60	9
DC LV to HV	150	25	3.8
Low Voltage Supplies	40	500	20
Cables (10 per frontend card)	77,000 ft.	0.3 / ft.	23.1
Clock distribution system	4	10000	40
VME crates	4	10000	40
VME control cards	4	5000	20
VME receiver cards	5	5000	25
Engineering	960 hrs.	75 / hr.	72
Technician	640 hrs.	50 / hr.	32
Total			597.1
30% Contingency			179.1
Total including contingency			776.2

4.3 Prototype Construction

To finalize details of the design, construction, and module testing procedures, we will build two 64 strip prototype modules in early 2007.[2] The scintillator will be extruded at the Fermilab/NIU facility in December 2006. We will do extrusions with two different designs for the scintillator strips. One is the nominal design, in which 1.2 mm diameter wavelength shifting fibers will be glued into a groove (see Fg. 8). The other is a design with a central hole that will accommodate a 1.8 mm diameter fiber. If the larger fiber produces sufficient light without glue, this design would greatly simplify the module construction.

The prototype module construction will be completed during the spring of 2007. During the summer of 2007, we will collect data with these modules at the Double Chooz far detector hall (Fig. 4). Measurements of the muon and singles rates in the hall will be extremely valuable in the final design of the electronics.

4.4 Detector Shipping and Installation

Table 7 summarizes costs for shipping the detector components and installation at the Chooz site.

Complete 64-strip detector modules will be packed and loaded into 40 ft. intermodal containers for shipping to the Chooz site. Extensive studies done while shipping the MINOS modules demonstrated that no additional environmental controls are necessary. The amount in Table 7 is based on a quote from Cargo International Logistics. We estimate that the near and far detector installations will each require two technicians for two months (i.e., a total of 8 technician months).

[2]This work is supported by an NSF supplement.

Table 7: Proposed budget for shipping and detector installation.

Item	Units	Unit Cost (dollars)	Cost in thousands of dollars
Shipping			50
Technicians	1280 hrs.	37/hr.	47.4
Total			97.4
30% Contingency			29.2
Total including contingency			126.6

5 Integrating Education and Outreach into The Outer Veto Project

The focus of the educational effort for this proposal is on mentoring undergraduate women. We see this as a positive step in addressing the "pipeline problem," where young women disproportionately leave the field of physics during their undergraduate years [14]. We believe that a program offering hands-on experience as part of an international collaboration doing a cutting edge physics measurement will be instrumental in attracting and maintaining women in the program.

The focus of our education plan plays to the strengths and interests of the proposers. The Chicago and Columbia groups have a well-established commitment to enfranchising women in physics. We note that two of the four PIs on this proposal are women. One of the three institutions is an undergraduate college. Our goal has been to develop a plan that is practical, leveraging the resources needed for the experiment for the purposes of educating young women in physics. The scope is such that the plan can be achieved within the three years of this proposal. We believe that this project will leave a lasting impact at Barnard College and on female students from Columbia and Chicago.

5.1 Developing Infrastructure for Barnard College

As the centerpiece of our plan, we propose to develop laboratory infrastructure at Barnard College, solidify the connection between the Barnard and Columbia physics departments, and develop ties between Barnard and University of Chicago. Barnard College is a 4-year liberal arts school for women, with about four physics majors per year. It is an independent institution with affiliations with Columbia University. Barnard's proximity to Columbia and access to its resources makes this collaboration with the Double Chooz group at Columbia viable.

In order to allow first-hand experience in hardware development and instrumental work at Barnard, the photodetector testing facility for Double Chooz will be set up in the new Barnard Physics Research Laboratory. This will be built as a collaborative effort between Mukherjee, Conrad, Shaevitz, a postdoc and undergraduates. Testing of the photodetectors will be carried out by Barnard and Columbia Physics and Astronomy majors, both during the semester as well as in the summers. To leverage this opportunity, during the summers, Barnard will provide free housing for its students involved in the project. Shaevitz and Conrad expect to be actively involved in the testing, thus in contact with the students performing the tests. A postdoc will also be involved.

The test equipment will be designed to be modular and flexible, so that it may be easily adapted for working with different kinds of photodetectors. The objectives are two-fold: (1) The test facility will have the immediate impact of setting up a working research laboratory at Barnard

College. This will give *hands-on* hardware experience to Barnard Physics & Astronomy majors, while at the same time allowing them to participate in a major international experiment. (2) The test facility will help develop infrastructure at Barnard, that may easily be adapted for other applications. Mukherjee is interested in using this setup for the study of photodetectors for future projects, such as VERITAS Phase II. Participation in this project will, therefore, not only have the benefit of having a major impact on undergraduate research and education at Barnard, but will also potentially enable the Barnard group to play a bigger role in future experiments.

We also plan to develop links between Barnard and the University of Chicago. A large group of undergraduates will participate in detector production and testing at the University of Chicago. During summers, Barnard undergraduates will be hired to work at the Chicago on the counters. Work at Chicago will allow students to broaden their horizons by visiting another research university where they will meet new faculty, and also by tours of nearby Fermilab and Argonne.

A number of publishable results will come from the phototube and counter testing. For example, a comparison of our protoype studies would provide valuable information for future experiments and could be published in Nuclear Instruments and Methods. We also plan to send Barnard undergraduates to the American Physical Society meeting each year to give talks on their results. This proposal requests funding to support this travel.

5.2 Undergraduate Participation in Calibration and Analysis

As the experiment is built and commissioned, we plan to maintain the involvement of undergraduates in the program. These undergrads will be drawn from Barnard, Columbia, and Chicago. Because of the short timescale for this experiment, Double Chooz represents an unusual opportunity for undergraduates to participate in all aspects of the experiment, from construction to data-taking to analysis. This program requires a multi-year commitment to undergraduates, which is also an effective technique for keeping women in the program. Furthermore, because of the small size of the outer veto group, and Double Chooz as a whole, undergraduates can have a large impact on the analysis, making the experience more rewarding. Within a small community it is also easier for students to build confidence in their skills.

Barnard undergraduates will be offered independent reading research courses during the academic year and direct participation in commissioning and running the experiment during the summers. Also, to draw the interest of rising physics majors, we will develop an exhibit for the Barnard physics department which will include a live event display. Mukherjee teaches Advanced Physics Lab (Phys BC3082) where students use scintillators/PMTs to carry out experiments to measurements such as the muon lifetime. The event display will be incorporated into teaching of this laboratory. These projects require computing, as is requested in this proposal.

Columbia and Chicago also plan to hire undergraduates from their institutions to pursue calibration and analysis on Double Chooz. These students have the option to write an undergraduate thesis on their research. Two current Chicago seniors are already writing senior theses on Double Chooz design studies. All undergraduates involved in the calibration and analysis of the detector will be encouraged to present their results at an American Physical Society Meeting. Travel and computing for the Chicago and Columbia students will be covered by the base grants and so are not included in this proposal.

Both the Columbia and Chicago groups plan to maintain undergraduate groups on Double

Chooz which are gender balanced. Both the Columbia and Chicago groups have a history of substantial participation by women. The Columbia neutrino group has historically been 50% women, at all levels, since 1996. Both groups have a strong history of female participation in past experiments (NuTeV, MiniBooNE, KTeV and Braidwood).

5.3 Budget for Education and Outreach

Table 8 summarizes the budget for the education and outreach efforts described above. The allocation for undergraduates will support two students during the first budget year, and one undergraduate during each of the following years. (We've assumed 10 hours per week during the school year and 400 hours for the summer.) Note that the Chicago and Columbia undergraduates involved in construction and testing of the outer veto detector have been included in the module construction budget (Table 5). Funds for construction of the PMT test station, travel, and computing have been included as described earlier in this section.

Table 8: Proposed budget for education and outreach. All items in this table are for Barnard College. The quoted costs for travel and undergraduate salaries include 53.5% overhead.

Item	Units	Unit Cost (dollars)	Cost (thousands of dollars)
PMT testing station			
Test stand construction	1	1000	1
Light source and fibers	1	15,000	15
Oscilloscope	1	5000	5
HV supply	1	1000	1
Undergraduates	2560 hrs.	13.7 / hr.	35.1
Travel	4	1500	6
Computing	2	2500	5
Total			68.1

6 Results from Prior Support

Barnard College (NSF PHY-0244809)

The Barnard group has been working mainly on the STACEE and VERITAS projects. These funds have allowed the PI to build an astrophysics research program at Barnard College, support a graduate student at Columbia University and several undergraduates at Barnard, participate in a major way in the development of STACEE, and initiate a research program on VERITAS. The Barnard group was also responsible for developing and maintaining the laser calibration system for STACEE (in collaboration with McGill University) using NSF support. In addition, the Barnard group has been active in the analysis of astrophysics data taken with STACEE.

The University of Chicago (NSF-PHY-0456688)

The Chicago group members has been involved in the KTeV experiment at Fermilab and the Braidwood Neutrino Experiment. Blucher has been spokesman of KTeV (E832) since 1997. His group has led the analysis of the direct CP violation parameter ϵ'/ϵ, and performed the recent determination of the CKM parameter $|V_{us}|$ based on measurements of the 6 largest K_L branching fractions and semileptonic form factors. He was also cospokesman of the Braidwood Experiment (with Mike Shaevitz of Columbia), and was coleader (with Gabriela Barenboim) of the APS Neutrino Study Reactor Working Group.

Columbia University (NSF PHY-05-00492)

The Columbia group has mainly been working on MiniBooNE. Prof. Conrad is co-spokesperson for the experiment and Prof. Shaevitz is the coordinater of the Kaon Working Group. MiniBooNE, a low energy neutrino experiment using the Fermilab 8 GeV proton booster accelerator, is set up to search for neutrino oscillation in the region of the LSND anomaly and to make precise measurements of neutrino cross sections. First results are expected soon. Also over the past several years, the group has been working on the design and simulation of the Braidwood reactor neutrino oscillation experiment.

7 Summary

In this proposal, we have described the strong physics case for the Double Chooz experiment. The next key measurement needed to elucidate the physics associated with neutrino oscillation is the determination or limiting of the θ_{13} mixing angle. Determining if $\sin^2\theta_{13} >\approx 0.01$ is critical both theoretically and experimentally for future progress. The two detector Double Chooz experiment is well positioned to be the first experiment to explore the region down to about 0.02 with good control of systematic uncertainties.

Recognizing the importance of the backgrounds to the sensitivity and robustness of the experiment, our group has proposed to construct the outer veto detector. This system is a critical component of the detector's strategy for reducing and measuring backgrounds. As an initial stage for this project, a supplementary award to the University of Chicago is being used to build prototype modules and to resolve small design issues, as well as to begin to prepare the infrastructure for large-scale module production. This proposal requests the funding needed to construct and install the full outer veto system. The proposal also requests funds to support additional involvement of undergraduates in the very exciting design, construction, and commissioning phase of the experiment.

The funding requests for this three-year proposal are summarized in Table 9. A detailed breakdown of the costs is given in previous sections and in the budget justification section. Although many prices are based on firm quotes, we have included a 30% contingency for all items except for education and outreach. The yearly budget is dictated by the delivery schedule for the near and far detectors (see below).

7.1 Plans/ Milestones

Since the Double Chooz experiment will use the existing experimental infrastructure from the previous CHOOZ experiment, the timescale for the first phase of the experiment using the far detector can commence fairly quickly. Initial data runs with the far detector only will allow early oscillation results and also provide a timely look at backgrounds and uncertainties. This early

Table 9: Proposed 3-year budget. We have assigned a 30% contingency, budgeted mainly in Year 3, to all items except education and outreach.

Category	Request in thousands of dollars			
	Year 1	Year 2	Year 3	Total
Module Construction	399.2	517.4	134.0	1050.6
Electronics	308.9	235.1	53.1	597.1
Shipping and Installation	0	43.7	53.7	97.4
Contingency (on above items)	109	100	300	509
Education and Outreach	47.5	10.3	10.3	68.1
Total	864.6	906.5	551.1	2322.1

schedule places a premium on also bringing the far detector outer veto system online in late 2008 followed by the near detector system in late 2009. With this timetable, Table 10 lists milestones for the construction project.

Table 10: Significant Milestones in Outer Veto Project

Target Date	Milestone
December 2006	Extrude scintillator for prototype modules
July 2007	Run prototype modules in Double Chooz far hall
September 2007	Begin Extrusion for Far Detector Modules
July 2008	Install Outer Veto system in Far Hall
September 2008	Begin Extrusion for Near Detector Modules
September 2009	Install Outer Veto system in Near Hall

7.2 The Double Chooz Outer Veto Collaboration Organization and Project Management

The Outer Veto will be built by a collaboration of the University of Chicago, Columbia University and Barnard College. The group members include at Chicago, Prof. E. Blucher and Dr. M. Worcester; at Columbia, Prof. J. Conrad, Prof. M. Shaevitz, and Dr. Z. Djurcic, and at Barnard, Prof. R. Mukherjee; Ed Blucher will act as overall Project Manager with Mike Shaevitz as Deputy Manager. Columbia and Chicago each plan to add an additional postdoctoral scientist and several graduate students. Also, as stated before, all three institutions plan to include undergraduates in all stages of the project through to data analysis and oscillation results. The project is of a size and type that fits well with being accomplished by a consortium of university groups. In addition, the plans are to use undergraduate students to help with construction and testing. These tasks combined with visits to the Double Chooz experimental site will provide unique opportunities for the students to gain hands-on experimental experience. Both Columbia and Chicago have extensive facilities and experience in mechanical construction as well as electronics design, testing, and commissioning. The module construction will be accomplished using a coordinated joint effort by these two groups. Parts will be constructed at both institutions with final assembly and testing setup at one site. The electronics and DAQ systems also lends themselves to a joint effort with a division of labor and different components being designed and produced at one of the institutions. This close collaboration of Chicago and Columbia will be further facilitated by the Columbia group's significant presence at Fermilab where the scintillator will be extruded. Exact responsibilities for the two groups will be worked out during the prototype construction and testing phase, but we expect the groups to work together on both the mechanical construction and electronics.

Barnard College in collaboration with Columbia has the responsibility for testing the M64s. As described, this work will be carried out mainly with undergraduates from Barnard giving them a wonderful opportunity to participate in a forefront experimental physics project from the initial prototyping stage to installation and commissioning. In addition, this part of the project will help build the experimental infrastructure at Barnard and give the faculty there a base to contribute to future projects.

We believe that our strong university consortium has the both the manpower and experience to accomplish the outer veto project. In addition, this project is a good example of how NSF can empower a set of university groups to participate in forefront physics projects outside of the usual national laboratory format.