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Design and Construction of the MTest Detector

A Thesis submitted in partial fulfillment of the requirement
For the degree of Bachelor of Science with Honors in
Physics from the College of William and Mary in Virginia

By

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(Honors)

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Williamsburg, Virginia
April 2009

Abstract

The MINERνA (Main Injector Experiment of the ν-A) neutrino detector is a fine-grained, fully active detector which is to be installed along the NuMI (Neutrinos at the Main Injector) beamline upstream of the MINOS (Main Injector Neutrino Oscillation Search) near detector at Fermi National Accelerator Laboratory. The goal of the MINERνA experiment is to improve understanding of neutrino-nucleus interactions in the 2 GeV -10 GeV energy region. Before the MINERνA experiment can gather useful data however, it must be calibrated. The primary calibration will be made using the MINERνA Meson Test Detector (MTest), which is essentially a smaller version of the MINERνA detector. Once constructed, the MTest detector will be installed in the Meson Test Beam facility at Fermilab, which will provide beams of protons, pions, and electrons at tunable energies. The patterns of energy depositions from interactions of each of these particles in the MTest detector will be used to optimize simulations of the particle interactions in MINERνA. This will provide the energy calibration for the MINERνA detector and help define distinguishing characteristics for different types of particles in MINERνA.

Acknowledgements

First, I would like to thank my advisor Jeffrey Nelson for allowing me to conduct this research and the endless assistance he has provided along the way. I would also like to thank Jonathan Stevens for aiding me through many of the technical aspects of the project. I would like to thank the team members of the High Energy Physics group, particularly Kevin Sapp and Ian Howley, for providing assistance and answering several of my questions. Lastly, I would like to thank my Honors Committee for taking time to read and evaluate my research, despite all delays in turning it in.

Contents

1. Introduction

1.1 Neutrinos

A neutrino is an extremely small fundamental lepton. It was first hypothesized in 1931 by Wolfgang Pauli, who observed that energy and momentum were not always conserved in radioactive decays. The theorized particle was named the neutrino, meaning "little neutral one" by Enrico Fermi in 1934. The first discovery of the particle fitting this description occurred in 1956 (the electron neutrino) [1]. Since then, much has been discovered about the neutrino. The neutrino is also the most abundant matter particle in the universe (the most abundant particle overall being the photon). The neutrino is only affected by the weak force, which allows it to pass through tremendous amounts of matter before any interactions take place. In fact, a neutrino at solar energies passing through a lightyear-long block of lead has a <50% chance of interacting. The two primary types of neutrino interactions are called charged current (CC) and neutral current (NC) reactions. A charged current reaction occurs when a neutrino exchanges a $W^{\pm}$ charged boson and a charged lepton exists in the final state (e.g. $W^{+} \rightarrow \mu^{+} + \nu_{\mu}$). Neutral current reactions occur under the exchange of the neutral Z^0 boson and results with an electrically neutral lepton in the final state (e.g. $\nu_{\mu}x \rightarrow x'\nu_{\mu}$) [2] [3].

1.2 Neutrino Oscillations

There are three known flavors corresponding to the three known varieties of charged leptons: electron, muon and tau. In 1998, it was discovered using the Super Kamiokande detector that neutrinos have a non-zero mass, and that neutrinos indeed have mass eigenstates in addition to flavor eigenstates. The flavor eigenstates can be represented as linear superpositions of the mass eigenstates.

$$|\nu_f>=\sum_{m=1}^{3} U_{fm}\,|\nu_m> \qquad [1]$$

$|\nu_f>$ represents the flavor eigenstate (ν_e, ν_μ, or ν_τ), $|\nu_m>$ is the mass eigenstate, and U_{fm} is the f,m element of the unitary matrix giving the mixing amplitude of the different states.

Prior to these results, it was concluded through the Homestake experiment, which tried to count the number of neutrinos coming from the sun, that either the expected number of neutrinos was wrong or neutrinos must oscillate between their eigenstates because the observed number of electron neutrinos was far less than the predicted number. The SNO experiment showed that it was due to neutrino oscillations [2]. The probability that one flavor eigenstate (a) will oscillate to another (b) is given by the equation:

$$P(\nu_a \rightarrow \nu_b) = |<\nu_b\,|\,\nu_a(t)>|^2 \qquad [2]$$

Once the proper variables representing the eigenstates are inserted and appropriate approximations are made, this equation reduces to the following expression.

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[eV^2]L[km]}{E_\nu[GeV]}\right) \qquad [3]$$

Here, θ is the mixing angle between the two flavor eigenstates and mass eigenstates, E_ν is the neutrino energy in GeV, and Δm^2 is the mass-squared difference of the neutrino mass eigenstates in eV^2 [4].

1.3 MINOS and MINERνA

One significant current experiment in neutrino oscillations is the Main Injector Neutrino Oscillation Search experiment (MINOS). MINOS consists of two detectors over 700 km apart: the near detector at Fermi National Accelerator Laboratory (Fermilab) and the far detector in Soudan, Minnesota. The two detectors are located at opposite ends of the Neutrinos at the Main Injector (NuMI) beamline, a high intensity beam of muon neutrinos. The experiment compares the nature of the beam at each end in order to determine if the neutrinos are oscillating. In particular, MINOS primarily compares the ν_μ charged current energy spectrum at the Far Detector with that of the Near Detector and takes measurements of Δm^2 and $\sin^2(2\theta)$ [5].

The near detector is used to predict the neutrino spectrum at the far detector. However, due to poor spatial resolution, it is unable to obtain an accurate measurement of incoming neutrino energies. Since all particles in the detector have some rest mass that is used in determining the total energy, the energy measurement will be inaccurate if the total number of particles is not detected. MINOS is unable to detect individual particles and the energy measurement is calibrated using simulations based on particle information from previous experiments. Another key issue with MINOS is inter-nuclear scattering. As protons and pions interact in a nucleus, they give off energy or create new particles, and therefore, MINOS will observe a different energy than expected, especially in detectors with massive nuclei (older detectors used primarily light nuclei). The Main INjector ExpeRiment for ν-A (MINERνA) detector is being constructed to address these issues. MINERνA is based on a fine-grained, fully-active neutrino detector that is to be installed along the NuMI beam upstream of the MINOS near detector. MINERνA will be able to visualize all final-state particles in neutrino-nucleus interactions and be able to determine the energies of incoming neutrinos with much greater accuracy than MINOS. The fine-grained detector MINERνA will be able to obtain a much more accurate value for Δm^2, and therefore provide better insight into the oscillatory nature of neutrinos.

1.4 MTest

Before the MINERνA detector will be entirely ready to collect data, certain information must be obtained, such as the response of the detector to various particles at various energies. In particular, the number of pions (π^+), kaons (K), and protons in the detector will greatly affect the detector's response. The key issue is in finding the energy of observed particles as a function of the observed pion energy, since more than 50% of the observed pion energy can be taken off by neutrons through secondary interactions. In order to determine this and calculate the incident neutrino energy, the MTest (Meson Test Detector) is being constructed. It is to be installed in the MTest test beam at Fermilab. The data from MTest will provide an energy calibration for the MINERνA detector and help define distinguishing characteristics for different particle types in MINERνA. Even fairly limited statistics will aid greatly in understanding the detector's response to pions [6].

1.5 MINERνA and MTest Design

MTest and the MINERνA inner detector are composed of several strips of triangular polystyrene scintillator with reflective coating, arranged in a pattern known as a plane of scintillator, shown in figure 1.

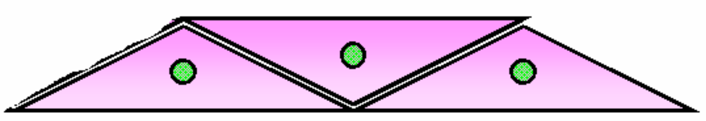

Figure 1: Cross-sectional Layout of MTest and MINERvA Planes.

MINERvA's inner detector planes will contain 127 of these overlapping strips of scintillator, while the smaller MTest will contain only 63. As charged particles pass through the scintillator, they excite electrons in the scintillator. As these electrons return to lower energy levels, they release photons with frequencies in the near UV range. As these photons move within the scintillator, they impact wavelength-shifting fibers embedded within the scintillator, which transform the UV radiation into green light. Some photons are lost due to absorption in the fiber. Others travel to one end of the fiber (the other end is mirrored) and are sent to a photomultiplier tube (PMT), which will give an output proportional to the energy deposition in the scintillator.

As particles pass through the scintillator, they pass through two strips per plane. Both scintillators will generate light that will pass down the fiber and be read by PMTs. This process is called light-sharing and it allows for a better understanding of where events occur within the detector. Another method used to improve resolution is to have three orientations of the scintillator. Half the planes in either detector will be oriented along a center axis, while the rest of the planes will be oriented $\pm 60^{o}$ in either direction from this axis. These techniques allow more precise measurements of the results of neutrino interactions within the detector [7].

2. Design Objectives

The objectives of this project are to construct initial MTest detector planes, construct the equipment necessary to make this an efficient and accurate process, and test which materials would be appropriate to use in its construction.

The MTest will consist of forty 1.07m x 1.07m square planes of scintillator, with 63 scintillator strips in each plane. Like the MINERνA detector, the strips will be of triangular cross-section with a base of 33mm and a height of 17mm, as in figure 2.

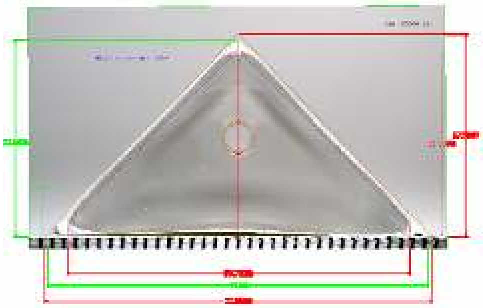

Figure 2: Cross section of MINERνA scintillator strip (33mm x 17mm).

The 1.07m-long strips will be arranged in the pattern demonstrated in figure 1, with 31 strips of scintillator on the bottom layer and 32 on the top. Each plane will be covered on the top and bottom with lexan skins and be bordered by side rails, a bottom comb, and a large upper comb made from foamed PVC. These side rails and combs form a frame for the scintillator. The upper combs have the additional feature of routing the wavelength-shifting fibers from the scintillator to the optical block at the edge of the comb. There will be two types of planes in the detector: x-planes and u/v-planes. X-planes will be oriented with the scintillator pointing horizontally, while the u/v-planes will be oriented with the scintillator ±60° from the horizontal in either direction, as in figure 3. There will be an equal amount of x and u/v planes, alternating positions in the detector.

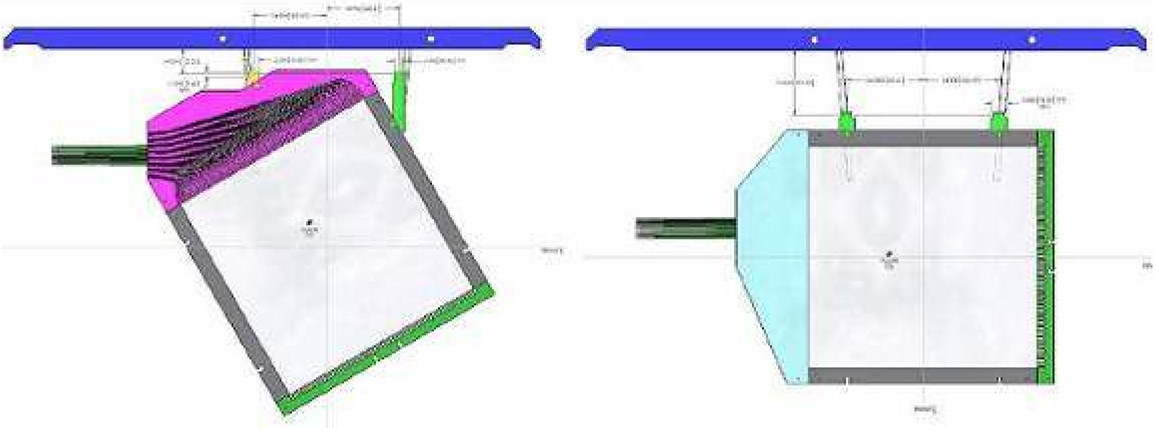

Figure 3: a u/v plane (left) and an x plane (right).

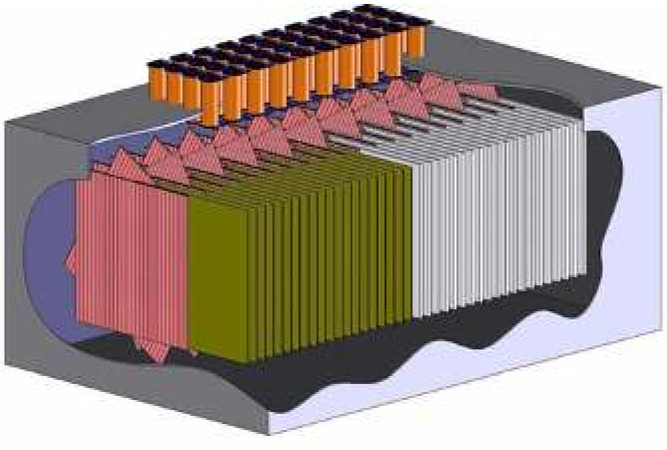

Figure 4: MTest layout with alternating planes.

The scintillators will contain wavelength-shifting scintillating fibers, which will be attached to ferrules and optical connectors so that the light generated from the energy deposited in each scintillator can be transported to photo-multiplier tube (PMT).

Each plane will be supported by two fire-retardant ABS hangers[1] glued to the side-rails, which are made from 18mm-thick foamed PVC. It is important that the epoxy used for this is strong enough to support the weight of the plane in all orientations. Glue

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[1] McMasters p/n 8586K281

tests were performed with various epoxies to determine which epoxy is most appropriate for this.

A melamine laminate table will also be constructed with pin fixtures and rails to enable efficient and accurate positioning of the scintillator during construction of planes. So far only the table-top had been assembled. We hope to assemble the first planes during the summer.

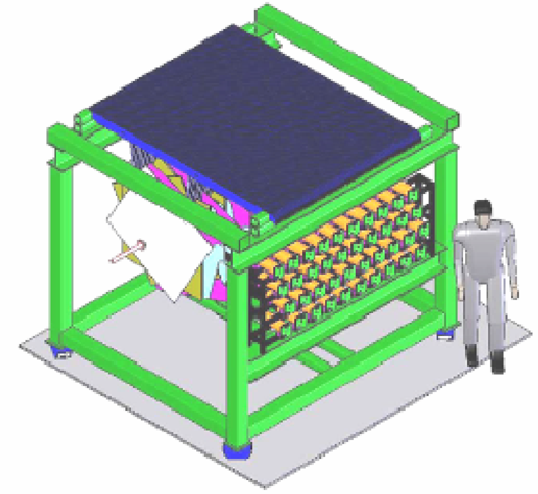

Figure 5: An image of the completed MTest design.

3. Procedures and Results

3.1 Hanger Material and Glue Tests

Tests were performed to ensure that the epoxy used to connect the side rails to the ABS hangers is strong enough to support each plane. Pieces of 12mm-thick foamed PVC[2], used to simulate the side rails, are cut such that 5 inches of the smooth (pre-cut) edge were exposed. This edge was then glued to the smooth edge of a 5 inch-long strip of ABS. This was done with two types of epoxy: gray and translucent epoxy manufactured

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[2] Celtec

by 3M[3]. Three “test strips” were made using each type of epoxy. The epoxy is allowed to completely harden for one week. Two test strips of each epoxy are used for the horizontal tension tests; the other two are used for the vertical tension tests.

3.1.1 Sheer tests

For each test strip, a hole was drilled in the center of the ABS component. The test strip was then laid flat on the plane-construction table, with the glue-line lining up along the edge of the table and the ABS component hanging off the edge. The strip was then harnessed to the table using C-clamps. A bucket was then suspended from the ABS strip using an s-hook, one end attached through the hole in the ABS and the other end securing the bucket. The load in the bucket was increased by increments of 2 kg until the test strip broke and. The maximum weight supported by each sample was then recorded.

Figure 6: The test sample fastened to the table for sheer test.

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[3] DP 190 2-part epoxy

Figure 7: Weights were added to the bucket until the test sample broke.

3.1.2 Tension tests

For each test strip, two holes were drilled. The first was a hole in the center of the ABS component. The other was a hole in the PVC component. Each sample was suspended from the monorail in the basement of Small Hall, with a bucket suspended from each sample. The load in the bucket was increased in increments of 2 kg until the test strip broke. The maximum weight supported was then recorded.

Figure 8: Vertical tension test setup.

3.1.3 Results

test type	epoxy type	weight supported (kg)
horizontal	gray1	82
(sheer)	gray2	76
	translucent 1	56
	translucent 2	64
vertical	gray	>102
(tension)	translucent	>102

Figure 9: Table of results from horizontal and vertical tension tests.

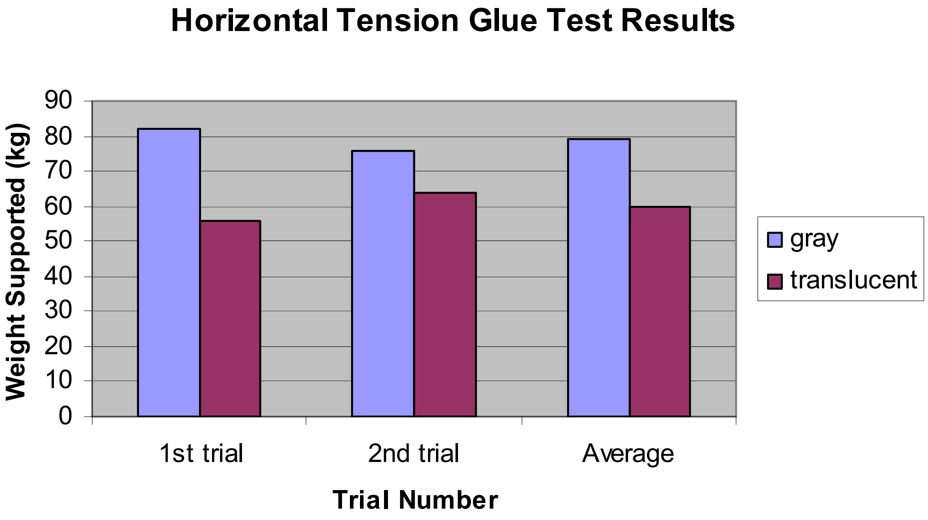

Figure 10: Results from glue tests.

A plane weighs approximately 20 kg, so based on these tests, either epoxy would be safe to use. Gray epoxy would be preferred because its viscosity makes it easier to apply.

3.2 Additional Glue Tests

Several additional glue tests were performed. These tests were performed primarily to test the strength of two different brands of epoxies: Ellsworth and 3M. The 3M DP190 gray and translucent epoxies had been the standard for MINERνA construction, but the comparable Ellsworth EP 1290 was far less expensive. However, it needed to be tested for the various connections the epoxy was used for before it could be approved for use. Although it was established that the Ellsworth brand was able to glue planks that could support an acceptable load, the 3M brand was able to support stronger planks, and therefore was the preferred epoxy.

3.2.1 Mini-Plank Tests

Each mini plank was constructed from seven pieces of ID scintillator, each 13.5 cm long. Four strips of scintillator were used on the bottom, three on top. The epoxy being tested was applied to attach the strips together, and was then used to attach a layer of 0.5mm-thick lexan to the top and bottom. The top layer was 11cm x 15cm, while the bottom layer was 15cm x 15cm. Six varieties of mini planks were used: 3M gray, Ellsworth gray, 3M translucent, Ellsworth translucent, Ellsworth translucent for scintillator to scintillator with 3M gray for scintillator to lexan, and 3M translucent for scintillator to scintillator with 3M gray for scintillator to lexan.

To perform each test, the mini plank was aligned with the scintillator strips parallel to the edge of the table, with half the mini plank hanging off the edge of the table. Two c-clamps were used to fasten the plank to the table, one attached at each corner, while another was used to attach the weight-holding bucket. This c-clamp was attached along the edge of the plank in the center. Weights were added to the bucket 2 kg at a time. When the weight of the bucket snapped the plank, or when the bucket could not physically hold any more weight, the weight was recorded.

Figure 11: setup for Mini-plank test.

type of test	weight (kg)
3M gray	48
Ellsworth gray	40
3M translucent	≥78
Ellsworth trans.	64
3M mix	≥78
Ellsworth mix	≥78

Figure 12: Mini plank test results.

For the results of this test, it is important to note that all mini planks that bore a load of 78 kg did not break, although hat does not mean that some weren't closer than others. The Ellsworth mix plank made several cracking noises, suggesting that the interior glue was starting to fail. The 3M translucent plank made only one crack, and the 3M mix plank showed no signs of weakening. The 3M brand is a stronger brand of epoxy, but since each MTest plane will only weigh 20 kg, the Ellsworth brand epoxies should be efficient for holding MTest planks together.

Similar tests were performed at Fermilab with full-sized planks. These tests also found that the Ellsworth brand was mostly acceptable, though there were some issues.

The key issue is that the Ellsworth is more viscous and difficult to spread evenly, which would lead to favoring the 3M brand.

3.2.2 PVC to PVC Test

Each sample for this test was constructed from two pieces of 12mm-thick foam PVC. Each piece had dimensions 20cm x 20cm. The pieces were glued together along the broad side. Once the epoxy had settled, two 2-inch screws were screwed into the narrow side of each board, one across from the other, 10cm from each corner. Two samples were prepared: one using 3M translucent and the other using Ellsworth translucent.

Figure 13: PVC to PVC test sample.

For the tests, the sample was hung by the top screws to an 80/20 rail. The weight-bearing bucket was suspended from the lower screws on the sample. Weight was added to the bucket until the sample broke or the bucket could hold no more weight. Results were then recorded.

Figure 14: PVC to PVC test setup.

The important results for this test were that neither sample broke. Each supported over 100kg in weight, much more than the weight of an MTest plane. Either epoxy would be fine to use for this purpose.

3.2.3 Lexan to PVC Tests

These samples were made by gluing a 20cm x 30cm piece of lexan skin to a 20cm x 20cm piece of 12mm thick PVC. The center of the lexan coincides with the center of the PVC, and the lexan and PVC were flush on two sides. A screw was inserted into the PVC on the narrow sides flush with the lexan. The two varieties of samples made were with Ellsworth gray and 3M gray epoxies.

The setup for these tests was very similar to the PVC to PVC tests. The screws were used to suspend the sample. The bucket was suspended from the sample using a clamp attached to the lexan. Weight was added to the bucket until the sample broke. The weight supported was then recorded.

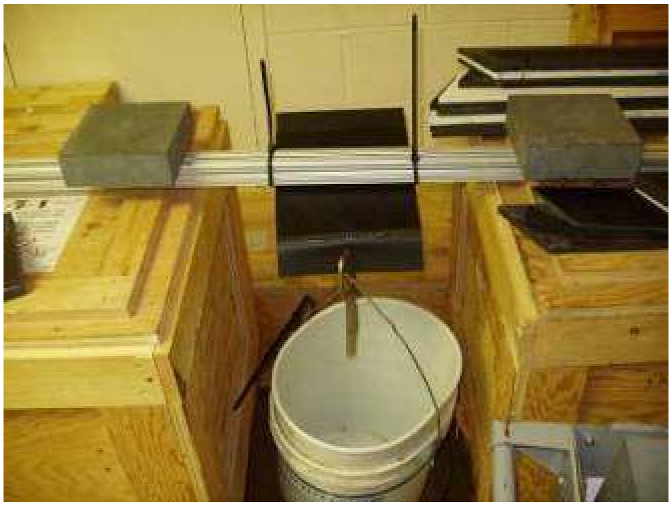

Figure 15: PVC to lexan test setup.

type of test	weight (kg)
3M gray	12
Ellsworth gray	8

Figure 16: PVC to lexan test results.

Important factors to note from the results are that the Ellsworth sample failed because of glue failure while the 3M sample failed because of a tear in the lexan. This difference suggests that the Ellsworth brand would not be ideal for connecting PVC to lexan.

3.3 Optical Block Light-Tightness Tests

An important part of the MTest planes that differs in design from MINERνA is the method of routing all fibers into a plastic connector block known as the optical block. Fibers will be routed directly from the scintillator to the optical block, which will route the fibers through black tubing to the ferrules. It is important that the connections from the optical block to the ferrule be light tight. Since it was expected that the glue used for attaching the tubing to the block would affect this, a test was performed using four different glues/epoxies to determine which would be best for attaching the tubing.

3.3.1 Procedure

A mock connector block is made out of PVC. It has eight holes, each the same thickness as with the standard block (0.25”). Black chemical tape is used to cover the bottom of each hole so as to prevent light from getting in. In four of the top holes, a 6.5” piece of tubing is inserted and sealed in using one of the four variations of epoxy. The four epoxies tested are 3M gray epoxy, 3M translucent epoxy, black RTV (room temperature vulcanizing agent), and clear 5-minute epoxy. Eight fibers connected to a ferrule are then inserted into one of these tubes. This connection is made light tight through the use of more tubing and black acrylic tape. A PMT (photo multiplier tube) and pico-ammeter are then used to determine the amount of light emitted by the fibers with lights on and off. This is repeated for each type of epoxy.

Figure 17: Setup of connector block with tubing, fibers, and ferrule.


Figure 18: Setup of Test with PMT and pico-ammeter.

3.3.2 Results

Epoxy	Current Generated (nA)	Current (photons/sec)
Gray	42	2019230
Translucent	44	2115384
5-minute	41	1971153
RTV	42	2019230

Figure 19: Connector block Light-tightness test results (same for lights on and off) .

As one can see, there was very little difference in the results. These current ranges are also on par with acceptable ranges for MINERνA light-leak tests, so any epoxy should be acceptable for connecting the tubing to the connector block. It is important to note that current changes were not detected when lights were turned off, so only one value was recorded per epoxy type. This is also important because it signifies that there was no leaked light. Since the translucent epoxy is the easiest to use, it is the preferred epoxy for this. Also, if the tubes are able to stay in the block without epoxy, epoxy may be avoided completely.

3.4 MTest Fixture Table Assembly

3.4.1 Table-top construction

The table-top was constructed out of four pieces of melamine laminate particle board. Two of these pieces have dimensions 49” x 26”, the other two pieces have dimensions 64.5” x 26”. The two longer pieces were attached to make a 64.5” x 52” board and the smaller pieces were attached to make a 49” x 52” board. These two were then attached to make a 113.5” x 52” table-top. The four smaller melamine boards were first laid out so as to make the top of the table face down. A metal screw-plate was placed where the four boards meet, and an additional screw-plate was placed at each crack between any two boards. On the center screw-plate, two screws are drilled through the plate into each board, for a total of eight screws. On each additional screw-plate, three screws were drilled through the plate into each board, for a total of six screws per plate. After each screw is tightly in place, the remainder of the crack space on the underside of the table was sealed with RTV (room temperature vulcanizing) silicone. When the silicon hardened, the board was flipped over so that the top was facing up. The cracks at the edges of the table were sealed with five-minute epoxy. After this epoxy hardened, the crack on top of the table was filled with Famowood brand high build epoxy coating.

After the top was assembled, the pin fixture was screwed into the center of the table. It contains 31 pins on each side, each 33 mm apart, so that the bottom layer of two planes can be assembled, one on each half of the table. Iron frames were attached along the ends of the table (shorter end). These are used along with metal wedges to hold the side fixtures in place once they are positioned correctly. Aluminum rails were screwed into the table just next to the fixture, parallel to the long ends. The sides of these rails form a 135° angle with the top of the table. This provides a frame so that both the top and bottom layers of scintillator can be glued accurately, with the top having one extra strip of scintillator.

Figure 20: the unfinished MTest fixture table.

Figure 21: A screw-plate with the appropriate number of screws.

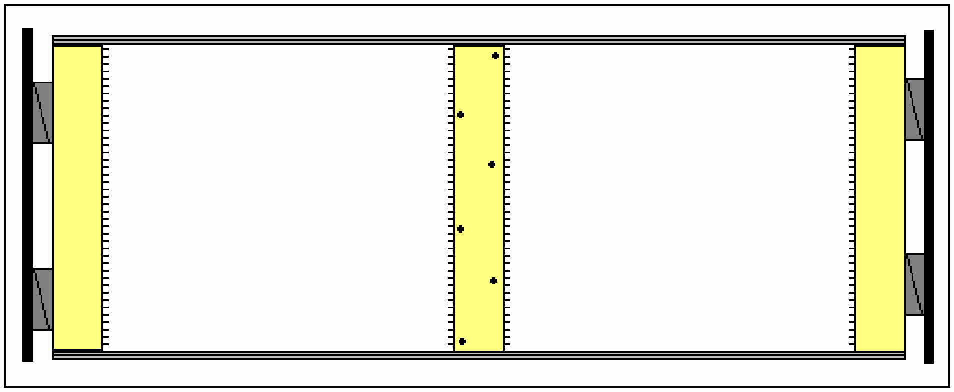

Figure 22: Layout for MTest fixture table.

3.4.2 Underside frame construction

The key component in the table's support structure is the 102" x 48" frame underneath, which is constructed out of 80/20 parts. The frame is important because it supports the seams so that a vacuum can be pulled on top. The parts used all have a cross-section of 1" x 1". Two of the pieces are 102 inches long. The other four pieces have a length of 46 inches. The four shorter pieces are on the "inside" of the longer two. Two of the shorter pieces are set flush with the longer pieces' edges. The other two are set 34" from either edge. Using the 90° connector pieces, the six 80/20 rods are connected in the proper places.

Figure 23: the underside 80/20 frame for the MTest assembly table.

3.5 MTest Plane Assembly

The following is the plan for assembly of MTest planes, although actual assembly has not yet begun. The primary reason that assembly could not begin is that parts that were being made in the machine shop were not completed in time for assembly this year. However, blank parts (laminated but not yet cut) were made and hangers and optical blocks are being made elsewhere. The fixture table was assembled and tested using scintillator parts, though no parts were glued.

3.5.1 Phase I

The assembly table and skins are cleaned using an air hose and kimwipes. Painter's plastic is then laid across the length of the table. The bottom skin is set into place and then coated with gray epoxy. The two PVC side rails and upper comb are then attached to the proper location and their slopes are coated with gray epoxy. The bottom layer of scintillator (31 strips 1.07m long) is placed on the bottom skin using the pin fixture for proper alignment. These strips are then coated with translucent epoxy before the top layer of scintillator (32 strips 1.07 m long) is laid on. The top skin is then coated with gray epoxy and laid on top of the scintillator. The above steps are repeated on the other half of the table. Another sheet of painters plastic is laid across the top of the planes, followed by a layer of a cloth material called batting. The painters plastic and batting are folded up to just cover the plane. A perimeter of vacuum tape is then made around the edge of the top of the table. This is used to attach a vacuum bag, which creates a tight seal around the plane when the vacuum is turned on. The vacuum is left on for at least 4 hours, and preferably over night.

Figure 24: A MINERvA plank sealed under a vacuum bag.

3.5.2 Phase II

The holes of each piece of scintillator are cleared of any excess material that may be covering them. They are then checked to see if a fiber can pass through from one end to another. If not, a metal wire is used to clean them out. Fibers of the specified length are then threaded through each scintillator hole and taped into place at the back end. The fibers are then color-coded to make them easier to keep track of. Fibers are wrapped in a sleeve of shrink tubing to light-seal them. Each bundle of eight fibers is then passed through a connector block to attach to the upper comb. Using a test ferrule and clip, the proper locations for the ferrules are marked. The ferrules are then injected with optical epoxy and inserted to the right depth on the fibers. Each ferrule covers eight fibers, except for one which covers seven. They are taped into position until the epoxy hardens. The hangers are now glued into the correct positions with gray epoxy.

Figure 25: Fibers in optical block.

3.5.3 Phase III

The connectors (the ferrules with fibers inserted) are polished using the polisher. The clip is then attached and the connectors are sealed into place. The glue machine is then used to inject optical epoxy into the scintillator in order to glue in the fibers. The uppers combs are sealed using canvex so that they are light-tight. The bottom combs are then glued into place using gray epoxy.

3.5.4 Phase IV

The side rails and bottom combs are sealed with black chemical tape to ensure light-tightness. Using a PMT and a light source, the plane is then tested for light leaks. When found, the light-leaking sections are coated with chemical tape. The connectors are sealed with protective tape when this is finished. When this process is finished, the plane is loaded into the crate to be sent to Fermilab.

4. Conclusions

From the glue tests, it was concluded that the gray epoxy is the preferred epoxy for gluing the hangers. In fact, the test strips breaking had to do with structural failures with PVC and not the gray epoxy. When the translucent epoxy test strips broke, only the glue was compromised. With each MTest plane expected to be about 20 kg, the translucent epoxy demonstrated that it can also support a plane. The vertical tests proved that vertical tension will not be an issue with either epoxy. Each test supported over 100 kg, which is heavier than an MTest plane, so supporting an MTest plane should not be an issue. Although both choices of epoxy would suffice, the extra strength demonstrated by the gray epoxy makes it the safer choice for attaching hangers to the planes.

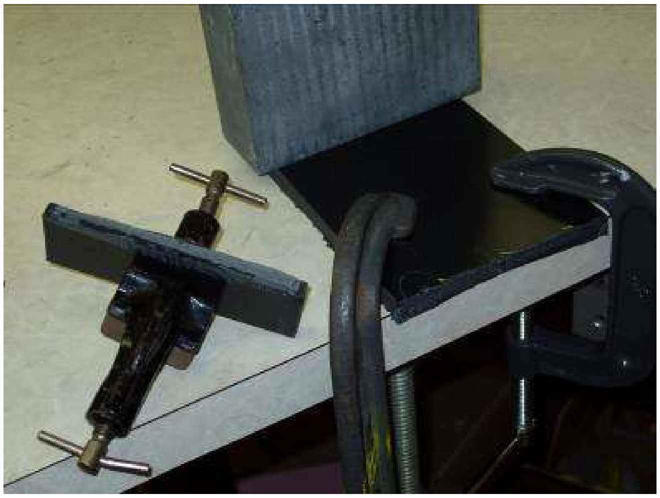

Figure 26: With the gray epoxy, damage was done to the PVC itself when the strip broke.

Figure27: Only the glue was damaged during the translucent epoxy tension tests

From the additional glue tests, it was determined that 3M epoxy is superior in almost all respects to the comparable Ellsworth products. Also, a later analysis of the epoxies found an irritant called Triethylenetetramine (TETA) in Ellsworth and not 3M. The Ellsworth was also much more viscous and difficult to spread evenly. For these reasons, the 3M brand was selected.

The connector block light-tightness tests showed that it doesn't really matter which epoxy is used to attach the tubing to the connector blocks. It is possible that no epoxy at all will be used, as long as the tubing can stay in on its own. If an epoxy were to be chosen, it would likely be translucent epoxy, since it is the easiest to apply.

5. Future Work

With the MTest assembly table mostly finished, it will need finishing touches before plane construction can begin. The underside frame will have to be attached to the table-top. Also, PVC parts from the machine shop must be finished. Since the PVC parts have been arriving from the machine shop and other parts have been shipped as well, the parts necessary for assembly should be ready relatively soon. The MTest fixture assembly table has been assembled, so full production of MTest planes can begin once all parts are ready.

6. References

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