→ A Topic in Low Energy Neutrino Scattering ← In Search of an Appropriate Detector

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ABSTRACT

High energy neutrino scattering (HENS) is relatively well explored as compared to low energy neutrino scattering (LENS). A collaboration is presently proposing the Minerva Experiment to further expand experimental data in the LENS range (energy <10 GeV), via use of the MINOS neutrino beam. This research proposes an appropriate augmented (outer) detector configuration for the Minerva detector. Data is provided by the Geant simulation. The angular distribution of muons is plotted as a function of their fraction of energy. With this information, a detector configuration is composed.

Another component of this research is visiting the MINOS far detector at the Soudan mine in Minnesota.

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Chapter 1

INTRODUCTION

The proposition of neutrinos was Wolfgang Pauli's attempt to save the conservation of energy from the experimental discrepancy of energy loss in beta decay. In Pauli's famous 1930 letter, he proposed the *neutron*: a small, neutral, ¹/₂ spin particle, to carry away the lost energy [1]. Pauli's suggestion was seriously considered only when Enrico Fermi incorporated Pauli's particle into a successful theory of Beta Decay in 1933 [2, p.23]. Fermi renamed Pauli's "neutron" the neutrino because Chadwick coined the neutral particle he discovered in 1932, the "neutron" [2, p.23]. Since the early 1930's, the neutrino has proven itself to be a mysterious particle, indeed – possibly bringing with it new physics.

1.1 Neutrinos & Oscillation

Neutrinos are the least massive particles in the lepton family (the mass cannot be directly measured.) They are neutral particles that interact via the weak interaction. Neutrinos pass through matter very easily. There are three types, or *flavors*, of neutrinos: electron neutrinos, muon neutrinos, and tau neutrinos. Each type of neutrino has an associated anti-neutrino. Also, as their names suggest, each neutrino is associated with a charged lepton. [2, pp. 46-48]

Experimental data (the Super-Kamiokande in Japan and the Soudan-2 in Minnesota, SNO in Canada) suggests that neutrinos change flavors [3]. For example, an electron neutrino can change into a muon neutrino, then back into an electron neutrino. This changing of flavor is called oscillation because the change in flavor isn't one way. A necessary condition for neutrino oscillations is that neutrinos have mass. This conclusion arises from quantum

mechanics. There may be a "mixing of masses." For example, when an electron neutrino is produced, it has a definite flavor eigenstate; however it does not have a definite mass eigenstate. Therefore, it may have a mixture of neutrino mass eigenstates; let's say a mixture of two mass eigenstates. Then the *probability* of the neutrino exhibiting each of these mass eigenstates oscillates with time.

The oscillation probability that a neutrino of mass eigenstate a will change into a neutrino of mass eigenstate b includes the difference between neutrino masses:

$$P(a \rightarrow b) = \sin^2(2\theta)\sin^2(1.27 \times \Delta m^2 \times L/E_{\nu}), (1)$$

Where E_{ν} is the neutrino energy, θ is the mixing angle between the flavors, and Δm^2 is the square of the mass difference [3]. The goal is to maximize the probability of detecting oscillation. For a given Δm^2 , an L/E_{ν} is called for to cause P to approach one.

1.2 Detecting a Neutrino

Neutrinos are never seen in a detector; only the products of their interactions interact with matter. The only evidence that a neutrino was present in the detector is the shower of charged particles produced from a neutrino interaction with a proton or neutron in the detector. The detector traces the paths, or tracks, of charged particles and determines their energies.

An ideal detector must have good (100%) acceptance for the particles it must detect. This means that it must be able to measure the energies and angles of particles produced in the interaction. In other words, it must *contain* the energies and tracks of the particles of the interaction. Detectors are designed to optimize their acceptance, amongst other things. They must be built with appropriate materials that can detect the sought interactions and provide data that can be analyzed to a desirable amount of accuracy and precision [4, pp.21-33].

As stated above, an ideal detector must be able to contain the energies and angles of particles produced in an interaction. The volume of the detector where events are contained is called the fiducial volume. Only events which occur in this region are considered because the detector can completely trace the tracks and energies of particles in these events. Particles produced in events outside the fiducial volume escape from the detector, thus the detector is unable to completely trace the tracks and energies of these particles.

If the detector is augmented, the fiducial volume increases. Augmenting the detector involves adding "outer detectors" which contain the escaping particles. Augmenting a detector is sometimes desirable because the outer detectors might be built of a different type of material. This will be the case in this research. Also, augmenting a detector can sometimes be less expensive than simply building a bigger detector, which will still have a fiducial volume.



Figure 1: The Fiducial Volume of a detector



Figure 2: Augmenting a detector

Chapter 2

THE MINOS & MINERVA EXPERIMENTS

The MINOS (Main Injector Neutrino Oscillation Search) experiment is currently under construction. The objective of the experiment is to detect neutrino oscillation: muon neutrino to tau neutrino. A beam of muon neutrinos will be sent from Fermilab (near Chicago) to the Soudan mine in Minnesota, where a 5400 ton iron detector will, hopefully, detect a *disappearance* of muon neutrinos, suggesting that they oscillated to tau neutrinos. The Minerva experiment is tied to the MINOS experiment because the muon neutrino beam will be produced at 5 GeV. This is a low energy beam when compared to earlier neutrino experiments [5]. In order to detect the oscillation of these lower energy neutrinos, it is beneficial to better understand how they interact with matter. This is the goal of the Minerva experiment.



Figure 3: The "setup" of the MINOS & Minerva Experiments

2.1 The MINOS Experiment

The MINOS experiment consists of a beam of 5 GeV muon neutrinos directed from fermilab to the Soudan mine. The neutrinos will first pass through a smaller detector near the target, called the near detector. This detector will provide data to calibrate the far detector, 735 km away. The near detector will provide information on the flux of the beam; this data will provide a more correct flux expectation at the far detector. Currently, simulations of the beam are being used to anticipate the flux. These simulations need to be checked because not too much is presently known about a beam of such low energy neutrinos. The beam will only be a few meters wide by the time it reaches the near detector. That is why this detector, 0.0025 sec later, it will be a few kilometers wide; which explains why the far detector is quite large.

The MINOS near detector consists of 280 iron planes. These planes are squashed octagons, with a width of 620 cm, a height of 380 cm, and a thickness of 2.54 cm. Between each plane is a 2.97 cm air gap.

The MINOS far detector is located 2341 ft underground. One advantage for the detector to be underground is that the detector is shielded from many cosmic ray muons which might enter into the detector. The particles which do reach the detector are detected by a veto shield, which covers the top of the detector. This shield traces muons coming in from above the detector, which are most likely atmospheric or from interactions in the rock. The far detector is currently being calibrated by testing the surrounding "noise." An example of "noise" is the incoming amount of muons originating outside of the detector, or by-product particles of the rock surrounding the detector (such as decay products or radon). This calibration will be useful when analyzing data from the detector. The far detector consists of 486 octagonal planes (numbered 0-485). Between the planes are plastic scintillator strips lined with fiber optics. The fiber optics pick up the electromagnetic radiation from the scintillator as charged particles pass through. The fiber optics are connected to a "MUX box" which contains a photomultiplier, and the light pulses are hence digitized [6]. The interaction of different charged particles in the scintillator has been previously tested so that particles can be identified. There is a magnetic coil through the center of the detector which gives information on the charge and momenta of particles in the detector. The motions of charged particles are deflected in a magnetic field. The direction and curvature of deflection, along with the magnetic field gives the momentum of the particle by the cyclotron formula:

$R \alpha p/B$, (2)

Where R = radius of curvature; p = momentum; B = magnetic field.

The magnetic field is not uniform over the entire detector because the coil is located in the center and the detector is not circular, so a map of the magnetic fields throughout the detector is needed when calculating of momentum.

The far detector consists of a huge amount of electronics. There are roughly 250,000 electrical connections; there are 486×192×2 fiber optics channels alone. Again, the detector is oriented in the direction of Fermilab. Positioning the far detector was an obstacle in itself because the cavern housing it is not straight underground, but slanted at an angle. A few neutrino interactions per day are expected to occur within the detector. This is reasonable because the beam width is thought to be a few kilometers by the time it reaches this detector.

The detector is designed to detect muon neutrino interactions. A *deficit* of muon neutrinos is expected. This would imply that the muon neutrinos oscillated to tau neutrinos. Oscillation is a probabilistic ideal, it is not

absolute. The detector is placed at a baseline which is approximately a maximum on the probability curve of muon neutrinos oscillating to tau neutrinos. Although it is at a maximum, there will still be a lot of muon neutrinos left in the beam, which have not oscillated. That is why it is expected that some muon neutrinos will interact in the detector.

It is interesting (at least to me) that the far detector is not capable of detecting tau neutrinos. Tau neutrinos are thought to be the most massive neutrinos [7]. The tau particle would be produced in a tau neutrino interaction, and taus last for a very short amount of time [8]. A more segmented detector would be needed to detect a tau neutrino interaction. It was initially proposed to place a lead detector (planes of lead sandwiching emulsion sheets) directly in front of the far detector to detect tau neutrino interactions, but the cost of the emulsion sheets was too high. If the MINOS experiment proves successful in detector. Also, the prospects of another detector, placed further north, may be a possibility.

The purpose of the MINOS Experiment is not to obtain the masses of the tau neutrino or the muon neutrino, but to find the difference in masses (Δm^2) . The difference in mass gives the lower limit on the neutrino mass, in this case the lower limit on the tau neutrino. If the differences between each type of neutrino masses are known, it is rather simple to place them experimentally in order of mass. Data from the Super-Kamiokande detector favor muon neutrino to tau neutrino oscillation with $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3} \text{ eV}^2$ at 90% confidence level [3]. It is hoped that data from the MINOS far detector will compliment the results of the Super-Kamiokande, this time with a controlled beam rather than cosmic rays.

2.2 Recent Research Relating to MINOS

The Super-Kamiokande collaboration in Japan studied the neutrinos which are a result of cosmic ray interactions. The Super-Kamiokande detector has detected a deficit in muon neutrinos since it began collecting data in 1996[3, 9]. The detector was 12.5 million gallon stainless steel detector, lined with 11,146 photomultiplier tubes, and filled with ultra-pure water [9]. The photomultipliers are used to gather Cerenkov radiation resulting as the particles of the neutrino interactions, with oxygen, depart, traveling fast than the speed of light in the water [9]. This result is in agreement with data from the Soudan-2, located in the Soudan mine. The Soudan-2 is a different kind of detector than the Super-Kamiokande. It is a steel detector, and much smaller to say the least. As a result, fewer events were gathered from it. These detectors are different from the MINOS detector because they took advantage of atmospheric neutrinos. The MINOS experiment is more controlled in that a beam of a specific type of neutrinos will be produced and directed to the far detector, where a deficit will more firmly suggest oscillation.

2.3 The Minerva Proposal

The Minerva collaborators have proposed placing a small $2m \times 2m$ detector 1m in front of the MINOS near detector [5]. The purpose of building the detector is to explore the characteristics of the beam and low energy neutrino scattering (LENS). The characteristics of the beam are very important when considering the interaction of the neutrinos with matter, specifically with the MINOS detectors. A better understanding of LENS is a beneficial tool when tuning simulations and when analyzing data. Simulations of the beam are preliminary; the goal is to obtain a more accurate understanding of the physics of the beam, which can be generated from the Minerva detector. The Minerva detector will be made of a light-weight scintillator, such as CH_2 . A light-weight scintillator is a desirable composition for the detector because it will not impede the particles of the muon neutrino interactions before the tracks can be traced and angles from the scattering are observed accurately. A denser, heavier detector (like steel) will cause the particles to scatter within the detector, and it would be quite hard to reconstruct any angles due to the neutrino interaction.

The detector will necessarily be augmented in some way. Since the scintillator cannot to stop many particles, it is not able to contain them. In order to contain the particles exiting the detector, an outer detector must be constructed. The outer detector geometry and composition is yet to be configured. It may consist of steel planes, sandwiching scintillator strips lined with fiber optics. The fiber optics would then be connected to photomultipliers, perhaps within MUX boxes as in the MINOS far detector. The outer detector will be steel because it is necessary to stop the particles in order to contain them. The inner detector is composed of scintillator to get initial angles and track particles from the interactions; the outer detector is composed of steel to stop the exiting particles and contain them.



Figure 4: An augmented Minerva detector

Chapter 3

THIS RESEARCH

This research consists of two parts. One part is augmenting the Minerva detector. The other part is the trip to the MINOS far detector in the Soudan mine. Both components have provided invaluable experience that will ever resound throughout my career...

In Search of an Appropriate Detector: Augmenting the Minerva detector

When augmenting a detector, it is important to consider the particles exiting from the inner detector. In this experiment, muon neutrinos are expected to interact with the protons or neutrons of the inner Minerva detector. The particles produced from the muon neutrino interactions will be muons, kaons, and pions. The major focus of this research is on the muons because they pass through matter more easily than the other two [11]. If any particle is likely to escape the Minerva detector, it is the muon. Thus, a configuration that will contain muons will also contain pions and kaons. For this reason I focused on muons: their angles, energies, and change in energy as they passed through matter (for this case, iron).

First of all, the maximum angle of muons versus their angles is needed to analyze the energies and angles of the muons in the detector (Figure 5). The source of this data is the Geant simulation. The number of events which take place at each angle and energy also needs to be analyzed to give an idea of the energy distribution of the muons. Here, a detector configuration is constructed after analyzing the average energy loss of muons as a function of distance in iron. The energy loss of muons in iron depends on the energy of the muons (Figure 6).



Figure 5: Maximum Energy VS Angle for Muons. Geant Simulation.



Figure 6: The average energy loss of a muon (in iron) as a function of muon energy. Source [10].

From the above information, the amount of iron needed to stop the fastest (5 GeV), sharpest angle (~13.5°) muon is about 3.5 m. The amount of iron needed to stop the slowest (< 1 GeV) muon with the widest angle (~120°) is about 0.8 m of iron. This information, alone, leads to this design of detector:



Figure 7: An outer detector configuration for the Minerva Detector.

Again, this is a slice of the outer detector because the outer detector will completely surround the Minerva detector. There is an immediate problem with this configuration. It will not work! The MINOS near detector is 1m behind the Minerva detector and the outer detector in this configuration takes up 3.5 m to the back.

A solution is flagging the exiting particles which enter into the MINOS near detector. The near detector will be able to contain even the highest energy muons. More data is needed to configure an outer detector geometry complimentary to this scenario. The points where the interactions occur with respect to the straight-ahead direction is very important. This will allow us to figure out how many muons are likely to enter into the near detector. This will have much bearing on the fiducial cut and the augmented detector setup. This is currently being done...

Appendix

The Minos Far Detector at the Soudan mine

My visit to the MINOS far detector was very exciting. There I learned how the detector is constructed and operates. The aforementioned descriptions of the detector are first-hand from my observations of the detector. While in the mine, my primary job was to string, strip, connect, and test bdot cables and their cards. Bdot cables provide data of the change in magnetic field over time for each plane. I gained most of my understanding about the beam and the electronics of the detector while there.

While at the mine, I received excellent instruction on the view of what is beyond the MINOS experiment. Currently, the standard model has the mass of the neutrino at zero. Since neutrino oscillation implies that neutrinos have mass, the standard model will have to be revised to implement massive neutrinos. Also, if neutrinos do indeed oscillate, this behavior is different from other leptons. If neutrinos have mass, their total mass accounts for a large portion of mass in the universe. Perhaps, they will provide insights into matter over anti-matter and the dark matter search. However, they are currently not believed to be the primary source of dark matter because they do not cluster. Neutrinos may also have an impact on theories of energy transport in the Universe; for example, the energy transport of supernovae.

Going to the mine provided me with hands-on experience, which makes the computer-work involved all the more fascinating. I am grateful for such an extraordinary opportunity.

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