

Development of a Novel Neutral Particle Detector

R. Tayloe and H.O. Meyer, November 16, 2005

1. Summary

We propose to build a prototype neutral particle detector (shown in Fig 1.) utilizing an innovative detector concept invented by our group at Indiana University (IU). The detector concept as well as the physics motivation behind it has been met with enthusiastic reviews by two panels of outside experts. While the basic idea has been demonstrated to be sound [1], there are technical details and possible applications that require further study. This requires prototyping for which outside federal funds are not available in the current budgetary climate. A successful outcome of this project will put us in a position to obtain research funding for a large detector for neutrino physics and for purpose-built devices for neutron detection.

This project makes excellent use of and expands on existing technical infrastructure at IU and at the IU Cyclotron Facility (IUCF). It will be well-aligned with the Commitment to Excellence (CTE) program by adding to the capabilities of the IUCF Low Energy Neutron Source (LENS) [2] and by providing training to students in the Applied Physics Program at IU.

For these reasons, this project merits support from IU. We are requesting a modest investment for a high likelihood of return. In this proposal we are requesting funds for the only the electronics portion of the prototype - funding for the mechanical parts has been obtained through another grant. While the full-sized version of detector has a very good chance of outside funding, it has been difficult to obtain sufficient outside funding to build this intermediate-sized prototype. If the funds for the electronics can be obtained, we would be able to be in an excellent position to propose the full-sized detector, without the need to perform additional R&D, by demonstrating that this novel detector performs as designed.

More details on this project, including background, methods, and expected results are expanded upon in the following sections.

2. Background

We are proposing to build a novel neutral particle detector. The original idea was conceived in order to build a large (approximately 10 ton) detector utilizing the technique for a neutrino experiment (“FINeSSE”) [3] to run at Brookhaven National Lab (BNL) or Fermilab. Both of these national labs are candidate sites for this experiment as they have the capability to deliver an intense beam of neutrinos.

In the proposed experiment, the neutrinos would occasionally scatter from neutrons or protons in the detector, and the detector would permit the products of those interactions to be tracked. The results would allow us to measure the otherwise elusive contribution of strange quarks and antiquarks to the spin and magnetism of a neutron or proton. These strange particles, though not primary constituents of normal matter, do appear and disappear fleetingly and may significantly influence the proton's structure. Probing their spin preference directly is a major goal of the international nuclear physics effort.

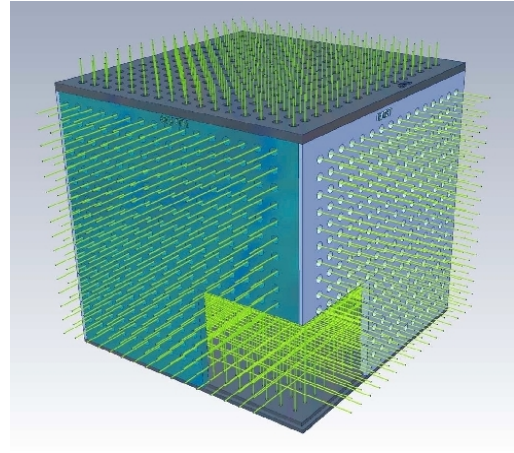


Figure 1: A schematic drawing of the proposed detector. The cube is approximately 50cm on each side. The photomultipliers, veto, and readout electronics are not shown. The interwoven grids of WLS fibers are visible through the cutaway corner.

A Letter of Intent was submitted to BNL in September 2004 and was reviewed by the BNL Program Advisory Committee. They found the physics “compelling” [4] and encouraged a full proposal. This project was also examined at a recent review in November 2004 by the NSF of our experimental nuclear physics program at IUCF. This committee of outside experts was also enthusiastic about the project and encouraged further investigation into other applications of the technique.

The detector for this neutrino experiment would be of dimensions 2.5m on a side and approximately 10 tons in mass. The estimated cost would be approximately \$2.5M. It is anticipated that most of this cost would be provided by the National Science Foundation (NSF) in the form of an MRI grant, and funds would come to IU to build the detector. We have met with the NSF and discussed this possibility. They were enthusiastic about the experiment and encouraged the submission of a MRI proposal. The next step is to get approval for the full experiment from BNL or Fermilab. This is underway.

While the basic idea has been demonstrated to work on a small scale [1] and in extensive simulations of the physics, the proposals to the national labs would be significantly strengthened by demonstrating that the detector will work as planned and can be built on a large scale. That is one of the main goals of this project. Even though this project is a good candidate for a major research grant to build a large neutrino detector, this research and development work is not a candidate for federal funds and requires funding of the type we are seeking here.

3. Applications

During the course of work on this detection technique, additional applications for this device, beyond detecting neutrinos, have become evident. The concept was invented by us and has been filed with the IU *Office of Technology Transfer* (docket no. 05035). By building the prototype proposed here we will be able to investigate these applications and tune the design parameters of the device to optimize performance.

This technique may be used for neutron radiography at the LENS facility at IUCF. In particular, it is well-suited for high-energy neutron radiography, which is useful for imaging low-density objects surrounded by high-density materials (such as nuclear devices). Thermal neutron techniques do not work in this application. We will use the prototype to investigate this possibility by testing the device in the neutron beam at LENS. This has the potential to improve the interdisciplinary neutron radiography program and, therefore, would enhance the CTE support of LENS and the associated advanced instrument program.

By demonstrating the sensitivity of the device to neutrons, we will be considering the applicability for national security. We are currently communicating with Crane NSWC about this possibility [6]. We will also measure the cosmic neutron flux which is important to understand because of the radiation damage from these neutrons to sensitive electronic equipment [7,8].

4. Education

This project will fit well with the education component of the IU CTE program by allowing undergraduate students in the applied physics program to take on individual subprojects required to build the detector. These projects would involve investigations to better understand the detector as well as teaching the student techniques in applied physics. There are many potential projects involved with understanding the spectral distributions of the emitted and absorbed light in fluorescence and light transport processes.

We have already demonstrated this principle as an undergraduate in the IU Science, Technology, and Research Scholars (STARS) program has worked with us over the last several years in the beginning stages of the project. After the detector has been investigated fully, we anticipate placing it in the advanced undergraduate lab course (Physics P451) where it may be used by students of applied physics to understand the workings of modern equipment and to investigate the physics of cosmic rays.

5. Methods

This project is motivated by the desire to build a detector of large mass to efficiently detect neutral particles such as neutrons and neutrinos, yet reconstruct the charged reaction products with sufficient precision. Common detectors such as drift chambers are precise yet do not provide a large mass. Typical large-mass neutrino detectors do not provide high precision. Our solution is to use a large volume of liquid scintillator, which provides mass for the neutral particle interactions, combined with a grid of wavelength-shifting fibers to capture the emitted light and to provide accurate coordinates of the interaction products. This is an innovative concept; a detector like this has never been built.

5.1. Principle of operation

The detector consists of a light-tight container, filled with a (mineral-oil-based) liquid scintillator. Wavelength-shifting (WLS) fibers, spaced 2.5 cm apart, immersed in the oil, collect the scintillation light created by charged particles, and guide it to photomultipliers. The arrangement of the WLS fibers is shown in Fig.2. There are three sets of fibers that are mutually orthogonal to each other. The resulting arrangement is invariant with respect to a rotation by 90° in any direction and allows for efficient reconstruction of tracks at any angle within the detector.

The light from a charged particle is detected by many fibers. This sharing of light by nearby fibers can then be used to provide coordinate information to reconstruct particle tracks. In effect, the device creates an image of the sub-atomic particle interactions.

5.2. Proof-of-Principle Tests

Preliminary tests of this detector scheme have been carried out using the 200-MeV proton beam at the RERP facility [5] at IUCF. The device tested was a box of dimensions $14 \times 13 \times 30 \text{ cm}^3$ (see Fig.3) with a 5 by 6 array of fibers oriented parallel to the long dimension and spaced 2 cm apart. Each fiber was connected to a pixel of a 4×4 multi-anode photomultiplier tube (for more details, see Ref. [1]).

For these tests, the 200-MeV proton beam was incident on the box, and could be moved vertically to scan the beam across the rows of fibers, and rotated around its long axis to study protons that intercept the fiber array at an oblique angle.

We found that the light from a 200-MeV proton track generates up to 17 ± 2 detected photoelectrons, quite sufficient for excellent performance of the detector. We were able to reconstruct the position and angle of individual proton tracks to 4.4 mm and 5.6° , respectively. These values are quite satisfactory for a detector of this type.

These tests results were successful and showed the promise of this detector technique, however, the relevance of these results to a large detector is somewhat limited because of the small size of the device and the fact that the fibers were oriented along only one direction. For this reason, it is desirable to increase the size of the detector and the number of fibers, and to arrange the fibers as described above to measure tracks in all three dimensions.

5.3. Design of the proposed detector

As the next step in the development of our detector scheme, we propose to build an intermediate-sized version of the detector that is small enough to be easily transported to different test environments, yet large enough to represent the basic features of a future, even larger version. This work will allow us to

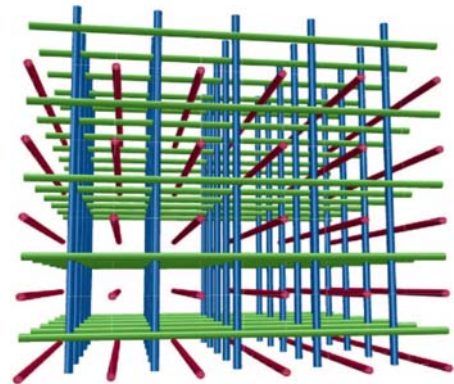


Figure 2: The geometrical arrangement of wavelength-shifting fibers inside the tank. The three sets of orthogonal fibers shaded differently for clarity.

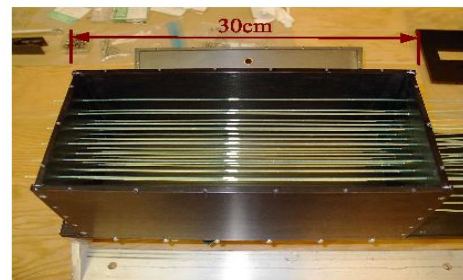


Figure 3: 'Proof-of-Principle' test setup. The detector is shown with its lid removed. The proton beam used for the test traveled perpendicular to the fiber

demonstrate tracking in three dimensions, to fully understand the detector response by comparison with a simulation, to study issues of triggering and calibration, and to develop the necessary track-reconstruction algorithms.

The proposed detector (shown in Fig.1) consists of a cubic container, 45 cm on a side filled with approximately 100 kg of liquid scintillator. We will weave an array of 16 by 16 WLS fibers between each pair of opposite sides for a total of 768 fibers. The fibers have a diameter of 1.5 mm and are 2.5 cm apart. The ends of the WLS fibers outside the container are coupled to clear optical fibers that in turn are aligned with the pixels of an 8 by 8 channel, Hamamatsu R7600-00-M64 photomultiplier. The readout electronics consists of an innovative system developed at IUCF as part of another major nuclear physics detector development project, recently completed successfully after attracting \$4.3M of new funds from NSF to IU. The decoded amplitude and time information from each photomultiplier is transmitted to the data acquisition computer for further analysis.

To distinguish primary charged particles (such as cosmic muons) from neutral particles entering the detector, a “veto” detector is required that completely surrounds the fiber detector. This veto layer will consist of plastic scintillator, read out by embedded WLS fibers.

6. Expected Results

The proposed detector will be used to demonstrate the viability of the method for the detection of both neutrinos and neutrons. To do this we will make measurements using protons, neutrons, and cosmic rays.

The results from this work will be:

Increased understanding of the workings of the device as a neutrino detector. These results will be used to strengthen our proposal for a neutrino experiment at a national lab. If that proposal is successful it will bring approximately \$2M to IU to build the large neutrino detector.

A design for a neutron detector to be used at the interdisciplinary LENS facility.

A measurement of the cosmic ray muon and neutron fluxes.

An opportunity for IU undergraduate applied physics students to be involved in cutting-edge research physics while learning the techniques and equipment used in the field of physics.

In addition, these tests will result in several published articles.

7. References

- [1] R. Tayloe et al., “A large-volume detector capable of charged-particle tracking”, submitted to *Nuclear Instruments and Methods*, (<http://www.iucf.indiana.edu/~rex/scibath.pdf>).
- [2] Low Energy Neutron Source, <http://www.iucf.indiana.edu/lens/>.
- [3] L. Bugel et al., “A Proposal for a near detector experiment on the booster neutrino beamline: FINeSSE”, arXiv:hep-ex/0402007; S. Brice et al., “The FINeSSE detector”, *Nucl. Phys. Proc. Suppl.* **139**, 317 (2005).
- [4] Letter from Thomas Kirk, Associate Laboratory Director, Brookhaven National Lab, September 19, 2004.
- [5] Radiation Effects Research Program: <http://iucf.indiana.edu/RERP/rerp/>
- [6] Kun Ma, IU Office of Technology Transfer, private communication, Jan 05.
- [7] J.F. Ziegler and H.Puchner, SER – History, Trends and Challenges, published by Cypress Semiconductor Corp., 2004.
- [8] M.S. Gordon et al., Measurement of the Flux and Energy Spectrum of Cosmic-Ray-Induced Neutrons on the Ground, *IEEE Trans. Nucl. Sci.* **51**, 3427 (2004).

8. Budget

We are requesting \$99.0k for the electronics portion of this project. The budget is shown in Table 1 and consists of \$74.0k for equipment and \$25.0k for personnel. These are the costs required to build the readout system for the prototype detector. This is the major cost for the prototype. Funds for the other components (mechanical parts, liquid scintillator, plastic fibers, etc) have been procured from the IUCF nuclear physics group NSF grant. The personnel cost is that required to design and build the electronics system. The expertise for this task exists at IUCF and would not require the hiring of new personnel.

Item	quantity	comment	total
PMTs, main	12	for main	21.5
electronics channels, main	768	768 for main	36.9
PMTs, veto	1	for veto	1.8
electronics channels, veto	64	64 for veto	3.1
PMT power supplies		parts	4.8
data acquisition computer and serial interface		parts	6.0
equipment subtotal			74.0
electronics design engineer	2	FTE months	25.0
personnel total			25.0
project total			99.0

Table 1: Budget for proposed detector project. Costs are in units of \$1000. (PMT="photomultiplier tube")