SciBath: A Novel Tracking Detector for Measuring Neutral Particles Underground

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The SciBath-768 detector is a prototype neutral particle detector offering high-precision reconstruction of neutrino and neutron events. It consists of a three dimensional grid of 768 wavelength-shifting fibers immersed in 82 liters of liquid scintillator. Initially conceived as a charged particle detector for neutrino studies, it is also sensitive to fast neutrons (1-100 MeV). Simulation results show 30% efficiency and 30% energy resolution for 1-10 MeV tagged neutron events. The apparatus has been commissioned and will be deployed in Fall 2011 to measure neutrinos and neutrons 100 meters underground in the Fermilab MINOS near-detector area.

I. MOTIVATION

A. Neutrino Interactions

The original motivation for the SciBath detector was to reconstruct 1 Gev neutrino neutral-current elastic (NCel) scattering events, allowing a direct measurement of the strange-quark contribution to the spin of the nucleon $\bar{q}$. The experimental signature for this interaction is a single low energy proton of typically 100 MeV kinetic energy, which has a range of approximately 10 cm in liquid scintillator. Accurate reconstruction of these 10 cm proton tracks is difficult in a 10 ton scintillator detector, which the small neutrino cross section (typically $\sigma \approx 10^{-38} \text{ cm}^2$) requires.

![FIG. 1: The FINeSSE detector as modeled in a GEANT3 simulation. The front cubic region contains a 19k-fiber SciBath detector. A muon range stack is located behind.](image)

The detector described here, SciBath-768, is a prototype of the vertex detector proposed for the Fermilab Intense Neutrino Scattering Scintillator Experiment (FINeSSE), which was designed to measure these 10 cm proton tracks using the SciBath technology. The full-sized detector proposed consisted of 19,200 wavelength-shifting fibers immersed in liquid scintillator of volume $(2.5 \text{ m})^3$. This design would increase the performance/price ratio for neutrino detectors and would allow the economic construction of a large, high-resolution device.
B. Neutron Detection

Ambient neutron fluxes are an important background for some experiments, especially low-rate underground experiments searching for dark matter or neutrinoless double-beta decay. However, these fluxes are difficult to predict. The SciBath-768 detector could aid these experiments by directly measuring fast neutron (1–100 MeV) fluxes. In general, fluxes of cosmic-ray muon induced neutrons have only been measured at a few sites [2]. SciBath-768 could be used to experimentally map out these fluxes as a function of depth and at a particular experiment location.

II. PRINCIPLE OF OPERATION

The SciBath design starts with a light-tight container filled with liquid scintillator. Wavelength-shifting (WLS) fibers are arranged with three sets of parallel, mutually orthogonal fibers arranged in a grid. Scintillation light from charged particles moving through this container is captured by the embedded wavelength-shifting fibers and is guided to multi-anode photomultiplier tubes (MAPMTs). The amount of light captured depends on the distance between the particle track and the capturing fiber in a well-understood fashion. Thus, by measuring the amount of light captured by each fiber the parameters of the particle track can be reconstructed. The symmetry of this fiber arrangement allows reconstruction of particle tracks at arbitrary angles with good efficiency. The energy deposited by a charged particle can be interpreted from the total number of photons recorded by all fibers.

III. PREVIOUS WORK

A. FINeSSE Simulations

A GEANT3 [3] simulation of the FINeSSE detector showed excellent reconstruction of neutrino events with energy and angular resolution of approximately 10 MeV and 100 mrad, respectively, for the physics events of interest. An event display from this simulation for a charged current quasi-elastic (CCQE) and a neutral current elastic (NCel) event is shown in Figure 2. In the NCel event, the single recoil proton is visible and well-reconstructed. The cross section from the CCQE event can be used along with the cross section for NCel scattering to generate a more accurate measurement of the strange quark contribution to the spin of the proton than could be obtained using the NCel scattering cross section alone. The CCQE events are easier to identify because the resulting muon creates a longer, more obvious track.

B. SciBath-30

SciBath-30 was a “proof-of-principle” device that was used to demonstrate the viability of the SciBath technology [4]. It contained 30 parallel wavelength-shifting fibers immersed in liquid scintillator. This device was tested in the Indiana University Cyclotron Facility 200 MeV proton beam. These tests allowed for the tuning of the optimal WLS fiber/liquid scintillator combination and a measurement of the position and angular resolution for 200 MeV protons. Figure 3 shows the resulting 5 mm position and 6° angular resolution, quite adequate for the FINeSSE experiment.

IV. SCIBATH-768

A. Detector Description

SciBath-768 is a prototype of the proposed FINeSSE experiment and consists of a (45 cm)³ cube containing 82 liters of liquid scintillator and 768 WLS fibers as shown in Fig. 4. The scintillator is a custom mix of mineral oil with 11% pseudocumene, and 1.5 g/l diphenyloxazole (PPO) with an emission wavelength in the 350–400 nm range.

The WLS fibers are arranged in three 16x16 grids that are mutually orthogonal with a 2.5 cm fiber spacing. They are 1.5 mm in diameter and shift light from ultraviolet (320–370 nm) to blue (410–480 nm). Both ends
FIG. 2: Event displays from a GEANT3 simulation of neutrino scattering events in the FINeSSE SciBath detector. The top plots show the XZ (top) projection and the bottom plots YZ (side) projections. A CCQE event with a muon and proton in the final state is shown on the left and a NC event with a single final-state proton is shown on the right. The boxes indicate individual fiber hits, the lines terminating with dots are the reconstructed tracks, and the lines with arrows show the true tracks and vertex.

of each fiber protrude outside the cube where one end couples to 1.5 mm diameter clear plastic optical fibers that routes the wavelength-shifted light to MAPMTs. The other exposed end of each wavelength-shifting fiber is coupled to a custom-built pulsed LED calibration system with one LED per fiber (see Fig. 5).

The readout electronics consist of 12 custom-built “Integrated Readout Modules” (IRMs), each with an integrated Hamamatsu (R7600) 64-anode MAPMT. These IRMs are located on the detector in two VME crate “shells”. Each IRM (Fig. 6a) utilizes flash analog-to-digital converters (ADCs) sampling at 20 MHz, five field programmable gate arrays (FPGAs), and an ARM9 microcontroller. The final cost of these readout electronics is on the order of $70/channel (including the MAPMT).

The MAPMT signals are first shaped by a “ringing oscillator” circuit as a front-end in the IRM to allow a time and charge measurement with one ADC channel. A typical MAPMT waveform as input to the flash ADC is shown in Figure 6b). The FPGAs provide zero suppression and buffering before data is shipped off via ethernet to a data acquisition computer for analysis.
FIG. 3: Position (a) and angular resolution measured in the SciBath-30 device.

FIG. 4: A schematic view with cutaway of the SciBath-768 cube and WLS fibers.

B. Current Status

The SciBath-768 detector and data acquisition (DAQ) system are currently assembled and operating. The first iteration of analysis and simulation software are also finished and in use. We are currently commissioning and calibrating with cosmic muon events and the LED system.

Figure 7 shows both a simulated and a detected (true) cosmic muon event. Here each WLS fiber (and PMT channel) records a “pixel” on the event display, where the box (pixel) size is proportional to the number of photons seen by that fiber. Note that in this figure only a preliminary calibration has been applied.

Ongoing work includes further calibration with cosmic muon and LED data, upgrading DAQ software, and developing particle identification algorithms. We are also preparing for a three month run this fall at Fermilab.
in the MINOS near-detector area.
C. Simulations

The detector is currently simulated with a GEANT4 \[7\] code which is used to predict the detector response to various incident particles. Cosmic muons typically result in a through-going track in the SciBath-768 detector. These tracks are easy to identify and provide a sample to use for simulation and reconstruction tuning.

Using this simulation, a track reconstruction method was developed using the method of least squares for
perpendicular offsets \[8\] and the MINUIT \[9\] minimization routine in ROOT \[10\]. This method demonstrated 3 mm position resolution and 5° angular resolution for through-going muon tracks.

A neutron in our scintillator will predominantly scatter elastically on protons generating short recoil proton tracks losing energy until it thermalizes and is captured via the \(n(p,d)\gamma\) reaction. This neutron capture generates a signature 2.2 MeV photon in a characteristic time of 186 \(\mu\)s. This characteristic signal of a prompt recoil protons followed by neutron capture may be used to tag stopping neutron events.

A simulation of the response of SciBath to a 2.2 MeV photon from a neutron capture event leads us to expect roughly 45 photons detected, as shown in Figure 8(a). Further simulation has shown that SciBath-768 will be able to use this signature to tag 1–100 MeV neutrons with efficiency and energy resolution as shown in Figure 8(b). In the 1–10 MeV energy range a 30% efficiency and 30% energy resolution are predicted. This evolves to approximately 10% efficiency and 60% energy at 100 MeV as it is more probable to lose some fraction of the neutron energy due to escaping particles.

![Distribution of the number of detected photons in SciBath-768 from a simulated 2.2 MeV neutron capture signal](image1)

![Simulated tagged neutron detection efficiency and energy resolution for 1–100 MeV (kinetic) neutrons.](image2)

FIG. 8: SciBath-768 tagged neutron simulation results.

### D. Future Plans

In the Fall of 2011, the SciBath-768 detector will be moved to and run 100 m underground in the MINOS near detector hall at Fermilab (Fig. 9). The goals for this run are threefold. First, the NUMI beam will allow for a demonstration of neutrino event reconstruction. In the three months that we plan to run at FNAL (two month livetime) we expect to see between 100 and 10000 neutrino events depending on the neutrino beam configuration (Table I).

| Beam Configuration         | \(\nu\) CC Inclusive | \(\bar{\nu}\) CCQEs |
|----------------------------|----------------------|---------------------|
| Neutrino, low energy       | 550                  | 100                 |
| Neutrino, medium energy    | 12000                | 1400                |
| Antineutrino: low energy   | 200                  | 30                  |
| Antineutrino: medium energy| 4000                 | 1300                |

TABLE I: Expected \(\nu\) / \(\bar{\nu}\) events in SciBath-768 in the MINOS near-detector hall in 2 months for all possible beam configurations. “Neutrino” and “Antineutrino” refer to the meson selection in the neutrino production target, producing a predominantly neutrino or antineutrino beam. The terms “low energy” and “medium energy” refer to the energy selection of the neutrino beam, with “low” providing a peak energy of 3 GeV and “medium” 6 GeV.

The second goal of the run is to measure the cosmic-ray-induced fast (1–100 MeV) neutron flux. From estimates based on FLUKA simulations \[2\], expected events rates are 20 cosmic neutron events per day. The third goal is to measure the neutrino-beam induced neutron flux in this location.
After a successful demonstration of the capabilities of SciBath-768 at Fermilab, we will next evaluate options to run in an underground lab at a greater depth to measure the fast neutron flux background relevant for future underground experiments.

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