CHANDLER R&D status

P. Huber, J. M. Link, C. Mariani, S. Pal, J. Park
Center for Neutrino Physics, Virginia Tech, Blacksburg, Virginia 24061, USA

Abstract. Reactor antineutrino fluxes can be measured to investigate neutrino oscillations including the possible existence of sterile neutrinos and conversely, the measurement of the neutrino spectrum and its composition over time indicates the makeup of the fissile material in the reactor. In view of this dual use potential, the CHANDLER technology has been proposed to realize ton-scale devices for the surface detection of reactor antineutrinos. Particular advantages of CHANDLER-type detectors are their excellent energy resolution, fine spatial granularity and a no-liquids design. During the initial R&D phase, a small prototype, called microCHANDLER, has been built and studied thoroughly using cosmic rays and radioactive sources. The outcome of these initial performance studies is presented here.

1. Introduction
Reactor neutrino experiments have now gone through many progressive generations; they are performing precision measurements of the neutrino oscillation parameters and are providing a hint of possible new physics of an eV-scale sterile neutrinos [1, 2, 3, 4]. Several short baseline experiments are planned or running to look for sterile neutrinos. Reactor neutrino detection can also be used for reactor monitoring [5, 6] and a clear correlation between the antineutrino signal and the state of the reactor was found in past experiments [7, 8, 9].

The CHANDLER detector has been proposed as a suitable short baseline neutrino detector which can operate at the surface, in close proximity to a reactor, with minimal shielding and without hazardous liquids, which is strongly preferred for safeguards applications [10, 11]. During the initial R&D phase, a prototype of the CHANDLER detector, called microCHANDLER, has been built at Virginia Tech. Detector technology, experimental setup and efficient neutron tagging in this prototype are discussed in the following sections.

2. CHANDLER technology
The CHANDLER technology is an evolution of the SoLi∂ reactor detector design [12] (efficient, low background neutron tag, high spatial resolution) with the optical lattice readout scheme originally proposed by Raghavan for the LENS solar neutrino detector [13]. This combination provides excellent energy resolution and improved neutron tagging efficiency, while maintaining the high spatial resolution which is critical to reduce the random coincident and fast neutron backgrounds that could otherwise swamp the inverse beta-decay (IBD) signal at an above ground location. The detector is configured as alternating layers of wavelength-shifting (WLS) plastic scintillator [14] cubes of dimensions $62 \times 62 \times 62$ mm$^3$ and $^6$Li/ZnS:Ag neutron detection sheets [15] which are 0.32 mm thick. In an inverse beta decay (IBD) event, the primary light from the positron is created almost exclusively in the scintillating cubes and it is released with a time constant ($\tau$) of about 9 ns. Light produced by the positron is transmitted by total internal
reflection along the cube row and column directions that run parallel to the sheets. Meanwhile
the neutron thermalizes and is captured on a time-scale of about 60 $\mu$s. Approximately 70% of
the neutrons capture on $^6$Li in the sheets producing a slow release ($\tau \sim 200$ ns) light pulse
in the ZnS(Ag) scintillator that is unique to neutron capture. Light produced in the sheets is
absorbed and re-transmitted by the wavelength shifter in the cubes and it is transmitted along
the cube rows and columns, just like the primary light. In this way the exact location of the
primary positron and secondary neutron capture are both known with the precision of the cube
dimensions (62 $\times$ 62 $\times$ 62 mm$^3$). At the edge of the detector, each cube row and column is
readout by two, 2 inch photomultiplier tubes (PMT), one on each side.

The CHANDLER detector has been proposed as a suitable short baseline neutrino detector
which can operate at the surface, in close proximity to a reactor, with minimal shielding and
without hazardous liquids, the latter is particularly important for safeguards applications.
[10, 11]. During the initial R&D phase, a prototype of the CHANDLER detector, called
microCHANDLER, has been built at Virginia Tech. Detector technology, experimental setup
and efficient neutron tagging in this prototype are discussed in the following sections.

3. Experimental setup

The microCHANDLER setup has been instrumented in 3 layers of WLS plastic scintillator cubes
interspersed with 2 sheets of $^6$Li/ZnS:Ag. Each layer of microCHANDLER has 9 scintillator
cubes arranged in a 3 $\times$ 3 array. Signals are readout in each plane by PMTs only from two sides
as shown in the left-hand panel of Fig. 1. PMT output signals are fed into a charge-to-voltage,
pulse shaping amplifier, with a 25 ns shaping time and amplification factor of 2, in order to
smooth peaks in the signal stream from fluctuations in the photon arrival times and to decrease
the noise present in the system. This allows us to make a precision measurement of the amount
of total light collected using a relatively low sampling frequency. We sample our signal with
a 16 ns, 12-bit digitizer. The choice of the 16 ns digitization is dictated by the fact that we
would like to reduce the data storage volume and 12-bit will guarantee a good dynamic range
in energy and adequate resolution. A schematic of the data acquisition (DAQ) process for the
microCHANDLER detector is presented in the right-hand panel of Fig. 1.

![Figure 1](image.png)

**Figure 1.** The left-hand panel: The microCHANDLER detector. Scintillator cubes and
PMT readout arrangements are shown here. Right-hand panel: The DAQ scheme for the
microCHANDLER detector.

4. Detector calibration

During the physics runs, the detector will be continuously taking calibration data. The muon
peak position in the pulse height distribution of a channel in the microCHANDLER detector
is used to determine the relative energy response of both the PMTs (gain) and the scintillator.
Each PMT has been characterized using this method in term of gain versus high voltage. The


Figure 2. Left-hand panel: Positions of muon peaks in the microCHANDLER detector before and after high voltage calibration. Right-hand panel: A typical Compton edge spectrum and the gamma lines as identified in the microCHANDLER detector.

Figure 3. Typical EM (left figure) and neutron (right figure) like pulse as recorded through the waveform digitizer.

difference between the PMT gains before and after the muon calibration method is shown in the left-hand panel of Fig. 2. In a large detector, muon tracking by the detector itself will allow to improve the accuracy of this method. This can be effectively studied with the next larger prototype, miniCHANDLER, which has 5 layers of $8 \times 8$ cubes.

Light attenuation in scintillator and losses at cube-cube interfaces result in a position dependence light collection in the cube rows and columns which can be measured in-situ using tracked muons. The absolute energy scale can be calibrated using radioactive sources, like $^{12}$B, $^{22}$Na etc. Preliminary studies have been performed using a $^{22}$Na source and corresponding Compton edges are have been identified (right-hand panel of Fig. 2).

5. Neutron tagging

Typical EM like (positron/gamma) and neutron like pulses are shown in Fig. 3 which are recorded with the waveform digitizer; these pulse have a shape difference at the 100 ns timescale and thus, the pulse shape discrimination (PSD) process is very simple: we use the ratio of area under the pulse and amplitude of the pulse.

For initial studies of neutron tagging the central cube of the microCHANDLER detector is used. The left-hand pabel of Fig. 4 shows the pulse area versus pul amplitude distribution for the central cube when a neutron source was placed on top of the detector centered around the
Figure 4. Left-hand panel: PSD distribution for the central cube of the middle layer. The inset view shows the overlap region in a zoomed view. Right-hand panel: Pulse amplitude distribution in top and bottom layers when a neutron candidate is identified in the middle layer.

central column of the microCHANDLER detector. Neutron-like events having lower amplitude of pulse and larger area under the pulse are quite distinct from the positron/gamma like events. But positron like events in the overlap region clearly outnumber neutron like events. This can be recovered by looking into the pulse information from the adjacent layers. Most neutron-like candidates are detected in the cube layers above and below the Li-sheet where the capture took place. As a result neutron-like event from the middle layer, i.e., within the region which is above the both red lines in Fig. 4, is first identified. Then we look for a neutron-like event in either the cube above or below, (see right-hand panel of Fig. 5) which gives a clear identification of the sheet where the neutron was captured.

The right-hand panel of Fig. 4 shows pulse amplitude vs area distribution for the top layer when a neutron candidate has been identified in the middle layer. We do not see the positron/gamma band in this distribution since the event has been identified as neutron event already in the middle layer. The bottom layer shows a similar distribution but has fewer total events compared to the top layer because of the placement of the radioactive source on top of the detector. This demonstrates that neutron tagging in this setup using pulse information from consecutive layers. The number of events appearing in the pedestal region in the top layer shows that the probability of assigning the wrong sheet which is less than 1%.

6. Background

A slightly different experimental setup was use to understand the background to neutron tagging in this detector. A Li-free ZnS:Ag sheet is placed between the top and middle layers whereas a normal, Li-loaded $^6$Li/ZnS:Ag sheet is still used between the middle and bottom layer. The neutron source are cosmic ray neutrons which are essentially uniform in the detector. In this exercise, if a neutron is identified in the middle layer then it must have captured in $^6$Li/ZnS:Ag sheet between the middle and bottom layer. The right-hand panel of Fig. 5 shows the pulse area versus amplitude distribution for the top layer when a neutron candidate is identified in the middle layer and only very few events show up in ten neutron signal region. Comparing the number of neutron-like events tagged in bottom and middle layer, which is not shown here as it is similar to Fig. 5, versus those tagged in the middle and top layer, shows that true cosmogenic neutrons outnumber fake neutrons by 50 to 1.
Figure 5. Left-hand panel: PSD distribution in top layer when a neutron candidate is identified in the middle layer. PSD distribution in top layer when a good neutron candidate is identified in the middle layer. Right-hand panel: In this case, the ZnS sheet between top and middle layers does not contain $^6$Li, i.e. these events are not due to neutron capture.

7. Summary
The performance of the microCHANDLER detector in terms of the purity of the neutron tagging is quite impressive. The rate of sheet misidentification is also very low in this setup, almost all neutrons are detected simultaneously on both sides of the sheet. Currently, we are commissioning the miniCHANDLER ($8 \times 8 \times 5$) setup and this detector is planned to be deployed at commercial nuclear power reactor in the summer of 2017.

Acknowledgements

References
1. K. Abe et al. Search for short baseline $\nu_e$ disappearance with the T2K near detector. Phys. Rev., D91(5):051102, 2015.
2. A.A. Aguilar-Arevalo et al. Improved Search for $\nu_\mu \rightarrow \nu_e$ Oscillations in the MiniBooNE Experiment. Phys.Rev.Lett., 110:161801, 2013.
3. Carlo Giunti and Marco Laveder. Statistical Significance of the Gallium Anomaly. Phys.Rev., C83:065504, 2011.
4. G. Mention et al. The Reactor Antineutrino Anomaly. Phys.Rev., D83:073006, 2011.
5. E. Christensen, P. Huber and P. Jaffke, Science & Global Security
6. E. Christensen, P. Huber, P. Jaffe and T. E. Shea, Phys. Rev. Lett. 113, no. 4, 042503 (2014).
7. A. Bernstein, N.S. Bowden, A. Misner, and T. Palmer. Monitoring the Thermal Power of Nuclear Reactors with a Prototype Cubic Meter Antineutrino Detector. J.Appl.Phys., 103:074905, 2008.
8. Yu. V. Klimov et al. Measurement of variations of the cross section of the reaction $\nu_e + p \rightarrow e^+ + n$ in the $\nu_e$ flux from a reactor. Sov. J. Nucl. Phys., 51(2):225258, 1990.
9. V. A. Korovkin et al. Measuring nuclear plant power output by neutrino detection. Soviet Atomic Energy, pages 712718, 1988.
10. Final Report: Focused Workshop on Antineutrino Detection for Safeguards Applications. IAEA Workshop, IAEA Headquarters, Vienna, Austria, Oct. 2008.
11. Thomas Shea and Julian Wichello. Proceedings of the first meeting of the ad hoc working group on safeguards applications utilizing antineutrino detection and monitoring. Technical Report SG-EQ-GNRL-RP-0002, IAEA, 2012.
12. P. Scovell, A. Vacheret, A. Baird, N. Ryder, A. Weber, et al., Low background anti-neutrino monitoring with an innovative composite solid scintillator detector, (2013).
13. C. Grieb, J. Link, and R. Raghavan, Probing active to sterile neutrino oscillations in the LENS detector, Phys.Rev. D75 (2007), 093006, hep-ph/0611178.
14. Eljen Technology, EJ-260 Plastic Scintillator.
15. Eljen Technology, EJ-426 Thermal Neutron Detector Sheet.