Remote Monitoring of Reactors: The Watchman Project

In 2001, Bernstein, West and Gupta [i] described a possible campaign to monitor nuclear fission reactions over large distances using arrays of Super-Kamiokande (Super-K) type water Cherenkov detectors, modified to include neutron-capture elements such as gadolinium. This modification would allow sensitivity to reactor and other low energy antineutrinos through the inverse beta decay interaction. In 2004 Beacom and Vagins [ii] identified a suitable water soluble gadolinium compound, and introduced the GADZOOKS! proposal to put gadolinium into Super-K. This would effectively transform SuperK into the world's largest antineutrino detector, fifty times larger than the KamLAND scintillator detector. More recently, there have been the proposals to include gadolinium doping in the water Cherenkov LBNE detector at Homestake, and the Hyper-K detector in Japan.

Both the fundamental neutrino physics community, with interests in supernova detection, proton decay and neutrino oscillation physics, and the applied antineutrino/non-proliferation community are interested in water Cherenkov technology. The latter community envisions the possibility of discovery or exclusion of small plutonium production reactors at hundreds of kilometer standoff, by looking for changes in the measured antineutrino flux in large antineutrino detectors. For all of these goals, gadolinium doped water detectors appear to be the most tractable, scalable approach to achieving the required detector sizes.

To date, reactor antineutrino detectors have largely employed liquid scintillator (e.g. KamLAND [iii], Double Chooz[iv], Daya Bay[v], Reno[vi]). With only ~1% as much light available, water Cherenkov detection is a significant challenge. The addition of a neutron absorber such as gadolinium is critical, because its enormous capture cross section, and the 8 MeV of energy deposited by the gamma-ray cascade from the de-exciting Gd nucleus enables sensitivity to the neutron generated in the inverse-beta-decay process,

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Since the inverse beta neutron is correlated in both position and time with the final state positron, backgrounds are enormously suppressed. (In an undoped water detector relying on Cherenkov light to generate a signal, the 2.2 MeV neutron signal from capture on hydrogen is essentially invisible.) As the detector size grows, the need for a non-flammable, environmentally benign and cheap detector material with good optical clarity increases. With this in mind the WATCHMAN (WATer Cherenkov Monitor of ANtineutrinos) project, is now being pursued by a University-Laboratory collaboration. WATCHMAN will experimentally demonstrate the potential of water Cherenkov antineutrino detectors as a tool for monitoring nuclear reactors over long distances, by deploying a kiloton scale detector several kilometers from a US nuclear reactor. While this standoff distance is not useful for near-term nonproliferation goals, the experiment would demonstrate the potential and scalability of doped water Cherenkov detectors. Couple with similarly sized detectors like KamLAND and Borexino, the detector will also be an important addition to the global supernova watch system, the only such element in the Americas.

The project consists of two main phases: background characterization as a function of depth, and actual deployment against a US nuclear reactor. In the initial phase of the project , the collaboration will study antineutrino background physics in water as a function of detector depth, using the Kimballton Underground Research Facility (KURF). Three event types, all cosmogenic in origin, are of particular interest. First, inelastic collisions between high-energy neutrons and oxygen nuclei in the water can result in high-energy gamma ray emission. If the neutron moderates and is captured on gadolinium the correlated pair will fake an antineutrino. Alternatively, multiple free neutrons can be produced by neutron spallation. The resulting neutron captures can also form correlated pairs. Finally, muons, or muon associated showers can also break apart nuclei, forming rare but long-lived radionuclides such as ^{9}Li, ^{8}He or ^{11}Li, which can decay via a correlated beta and neutron. If the mean time between muons is relatively short compared to the lifetime of the isotope, a simple veto accompanying each muon won't mitigate these events.

The second phase of the project involves deployment at a US reactor. Several sites in the US are under consideration, and a trade study is well underway, seeking to optimize cost by considering the effects of reactor power, overburden, detector size and standoff distance at each location.

The possibility of extending the reach of the scalable water based technology to antineutrinos has led to considerable interest in the WATCHMAN project from the fundamental neutrino physics community. As a result, many academic groups taking an active role in WATCHMAN - as well as the other water Cherenkov proposals such as Hyper-K and LBNE – since the latter include neutron detection as an option using gadolinium doping. The goals met by this project are thus broader than the nonproliferation technology demonstration itself, and will have a strong benefit for basic physics. R&D efforts are focused on improving proton decay and neutrino background discrimination, sensitivity to antienutrinos in long baseline neutrino oscillation experiments, improved photon detection and timing with the continued development of large area flat panel micro channel plates [vii], and at the largest scales vastly improved sensitivity to supernovae, extending well beyond the galaxy. A demonstration at the kiloton scale is an important, achievable step towards the deployment of multi-hundred kiloton detectors or detector arrays for nonproliferation and basic physics.

As a practical matter, the realization of "arrays of Super-K type detectors" as foreseen by Bernstein et al. lies a ways in the future, but along a straight path that is, at least in principle, relatively easy to traverse. The basic applicability of large water Cherenkov detectors has already been proven for many pure physics applications, so that the technology is being built on a firm foundation. The WATCHMAN project is likely to be the world's first attempt to extend this technology to kiloton scale detection of antineutrinos, and will give the physics and nonproliferation communities a detailed understanding of the capabilities of large-scale, non scintillator based detection of antineutrinos.

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[ii] "Antineutrino Spectroscopy with Large Water Cerenkov Detectors", J. Beacom, M. Vagins, Phys. Rev. Lett. 93 (2004) 171101
[iii] "Precision Measurement of Neutrino Oscillation Parameters with KamLAND". The KamLAND Collaboration. Phys. Rev. Lett. 100, (2008) 221803
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