A History of Applied Antineutrino Physics

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Abstract

Experimentally, the idea of monitoring reactor power and fissile content with antineutrino detectors was first pursued in earnest by a Russian-Ukrainian collaboration in the 1980s, using the Rovno reactor as the source of antineutrinos. Since then, technological advances and improved theoretical understanding of reactor antineutrino emissions have led to ever-more precise extraction of parameters of interest for nonproliferation and cooperative monitoring, and increasingly frequent, ambitious and successful deployments of detectors with reactor monitoring capability. As a result of these international, technologically diverse efforts, it is now appropriate to speak of a maturing field, 'Applied Antineutrino Physics', in which antineutrino-based methods are being developed for nuclear nonproliferation and disarmament treaty verification purposes. In this article, I will survey the history of this field and offer a perspective on select recent developments.

1 Introduction

After the prediction of the neutrino by Pauli, the subsequent search for experiments to discover and measure the properties of neutrinos converged naturally on the copious man-made (anti)neutrino source, nuclear reactors. Thus, as is well known, the neutrino was first directly detected by Reines and Cowan using a plutonium production reactor at Savannah River [1]. Perhaps the earliest explicit, if laconic, published reference to antineutrino-based reactor monitoring is to be found in the 'Neutrino 77' conference proceedings, in a talk by Mikaelyan entitled "Neutrino Laboratory in an Atomic Plant (Fundamental and Applied Researches)" [2]. The article noted that the increasing number and thermal power of reactors worldwide made monitoring with antineutrinos both achievable and potentially useful. The author laid out the research program with a casual economy: "This technique.. will be sufficiently important from the point of view of the control on the leakage of fissing materials and on nonproliferation of nuclear weapons, and for the economics of nuclear fuel recycling. More detailed consideration of these problems at this conference seems to be irrelevant".

While for the most part irrelevant for a conference focused on fundamental physics alone, an attractive feature of applied antineutrino research is its already proven ability to foster cooperation among diverse countries, a necessary ingredient in any successful nonproliferation and arms control enterprise. Similar to the productive lineage of post-Cold-War engagement by Russia and the United States on technical nuclear nonproliferation research in the Lab-to-Lab programs [3,4], applied antineutrino physics provides a broad avenue for cooperation among countries in an area of general international nonproliferation and physics interest.

A loose natural division of the conceptual framework for this area of research is between the 'near-field', defined as within one kilometer of the reactor, and the 'far-field', for monitoring beyond 1 kilometer. In the near-field regime, detector sizes are small enough, and total detected event rates may be made high enough, to permit estimation of the hour-to-hour or at least day-to-day operational status of the reactor, and an estimate of the relative or absolute thermal power of the core to within a few percent with day to week integration times. Also in the near-field, the total inventory of fissile material in the reactor core can be either estimated or constrained using spectral or rate-based measurements of antineutrinos. These measurements can be made with $\sim 1-10$ ton detectors, with the latter size required at the outer limits of the near field.

A more restricted but still compelling set of capabilities lies in the far field. In this domain detector sizes range from kiloton-scale to megaton-scale, where the larger mass is required for sensitivity to $\sim 50\ MWt$[a] reactors at distances of about 200 kilometers. (Higher power reactors are somewhat easier to detect by other means.) Here sensitivity is defined as discovery or exclusion of unknown reactors in a geographical region, using rate-only measurements, or verification of the declared operational power profiles of known reactors. To surpass the 200 km standoff limit, further study would be needed on suppression of backgrounds, arising from depth-dependent muogenic backgrounds, ambient radiation and reactor and geological antineutrinos. At minimum, suppression would be needed for the limiting background of antineutrinos arising from the world's reactors, by reconstructing the direction of the antineutrino in large detectors.

In principle, the distortions imprinted on the antineutrino energy spectrum by antineutrino oscillations could also be used to constrain the standoff distance of the reactor. However, this latter goal is much more difficult to achieve, since it places even more stringent demands on detector energy resolution and total detector mass.

Developments in near-field and far-field research have followed different paths, owing to the different technological problems that confront each domain. In the following sections, we provide a historical overview of how these developments occurred for each monitoring regime, following by some perspective on the future of this exciting and active area of research.

2 The Near-field

Figure 1 shows a chronology of important events in the history of near-field monitoring.

As discussed in the introduction, the first record I can find of antineutrino-based reactor monitoring is in the proceedings of the Neutrino '77 conference in Baksan [2]. Beginning in the mid 1980s, the first experimental effort to demonstrate the monitoring concept was performed at the Rovno Atomic Energy Station in Kuznetsovsk, Ukraine [5,6]. Rovno acheived all of the monitoring goals found in the Neutrino '77 article. The experiments demonstrated near–real-time sensitivity to the reactor core status, provided a daily estimate of the relative thermal power output of the reactor, and, most importantly, demonstrated sensitivity to the so-called 'burnup effect'. Burnup is a term of the art in nuclear engineering, effectively describing the amount of fissile material that has been consumed during reactor operations. In reactor neutrino physics, the burnup effect refers the variation of the measured antineutrino rate and spectrum that arises from the evolving mixture of plutonium and uranium isotopes in the core as the reactor proceeds through its normal operational cycle. Since the number of detectable antineutrinos emitted per fission varies with isotope, the antineutrino emission rate changes by some 10-15% over the course of a reactor cycle as the uranium is consumed, and as plutonium is produced and consumed. The degree of variation is determined by the reactor fuel composition, the core type, and the fuel management strategy over the course of the cycle. As the Rovno experiments proved, the antineutrino spectrum emitted by a Pressurized Water Reactor (PWR) using Low Enriched Uranium (LEU) fuel is measurably

[a] the abbreviation for MegaWatts thermal, a measure of the reactor power.

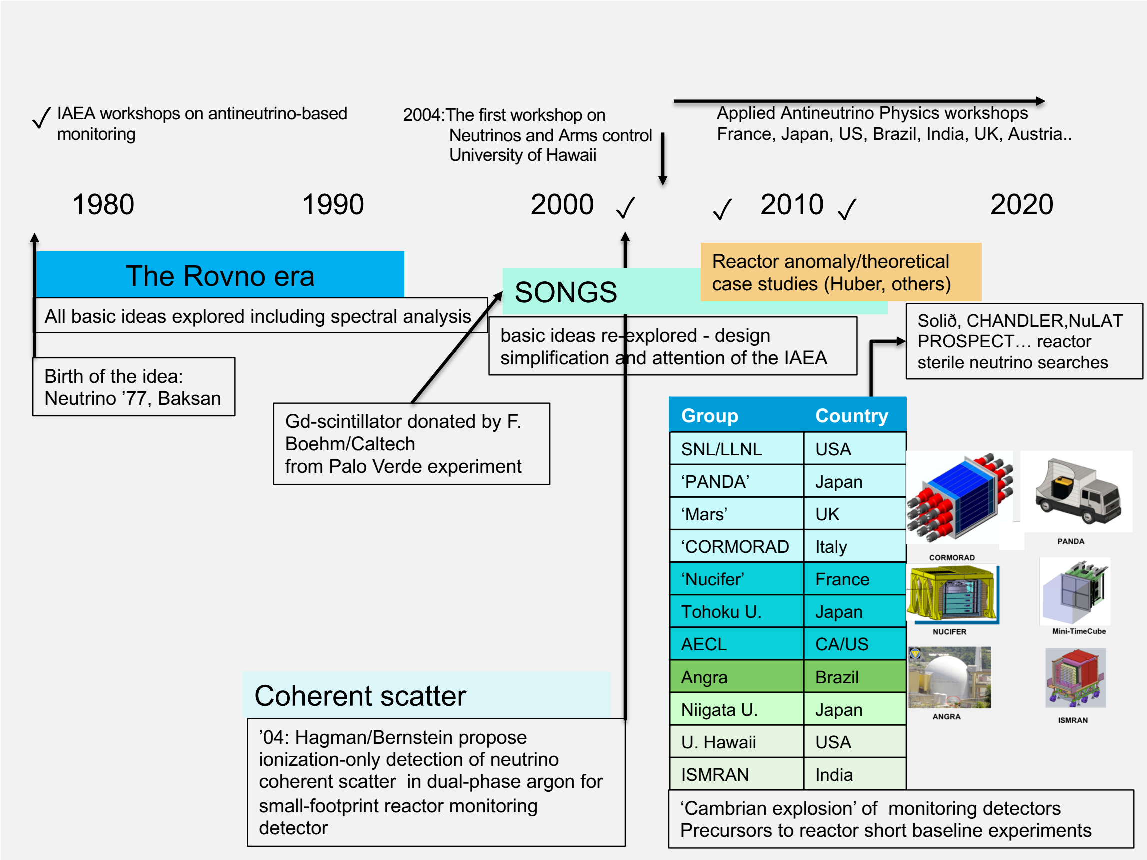

Figure 1 – A chronology of significant events in the history of near-field monitoring.

effected by burnup, with the spectrum from the principal fissioning isotope, ^{235}U being harder than that of the next most important contributor to fission, ^{239}Pu. Figure 2 shows the ratio of the antineutrino energy at the beginning and end of the cycle, with the expected hardening manifest. For the specific case of Rovno, the spectral variation arose from the net consumption of 521 kg of fissile material (both plutonium and uranium) over the course of the fuel cycle. The Rovno group independently estimated fuel consumption from a reactor simulation based on the plant's thermal power records, and found a value of 525 $\pm$ 14 kg, close to that implied by the measured antineutrino spectral change.

The seminal experiments at Rovno showed that the monitoring concept could work. While unusual compared with what is available at most reactors, the Rovno configuration was essentially ideal from a monitoring perspective. The detector was deployed directly beneath the reactor core, providing excellent shielding from muogenic backgrounds at a conveniently close location - 18 meters directly below the core center and 35 meters below the Earth's surface.

As the Iron Curtain was slowly being drawn back in the 1990s, Russian scientific results were not readily available in 'the West', so that the lessons of Rovno were relatively slow to penetrate in the U.S. and Europe. Independently of the Russian work, an experimental and theoretical program was undertaken in the U.S. jointly by Sandia National Laboratories and Lawrence Livermore National Laboratory in the first decade of the new millennium. Laboratory scientists performed a series of experiments at the San Onofre Nuclear Generating Station (SONGS) in Southern California, with the explicit purpose of demonstrating a reactor monitoring capability that could be relatively easily deployable, for use in the International Atomic Energy Agency's reactor Safeguards regime [7]. Safeguards is defined in this context as a set of accounting and measurement methods and protocols, aimed at detecting diversion of fissile materials from the civil nuclear fuel cycle into weapons programs. These techniques have evolved gradually over the decades since the IAEA's inception. Proposed new measurement methods, such as antineutrino-based monitoring, must be subject to a series of formal reviews by the IAEA in order to be accepted into the monitoring regime.

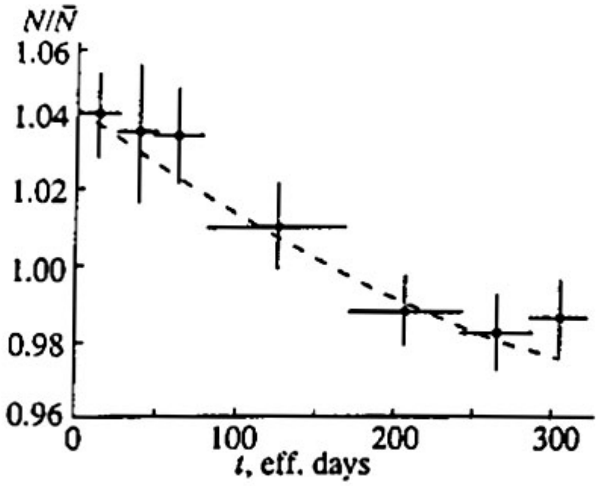

Figure 2 – The evolving antineutrino rate N, versus time in days, relative to $\bar{N}$, the mean value of the rate, as measured in an experiment at Rovno [5]. The gradual drop in the relative rate, arising from the increasing fraction of plutonium in the core as the reactor proceeds through its fuel consumption cycle, is clearly seen in the data (points with error bars) and confirmed by a model of the reactor core (dashed line).

The SONGS detector was deployed in the reactor's 'tendon gallery', an annular room that lies directly under the containment dome, which allows access to steel reinforcement cables that extend through the containment structure. The gallery is 25 meters from reactor core center. Many civil reactors have tendon galleries. They are well suited for deployment of an antineutrino detector because the large, vacant space is rarely accessed by plant personnel, and because of the muon-screening effect of approximate 10 m.w.e. earth and concrete overburden. Like the Rovno detector, SONGS used gadolinium-doped scintillator for its measurement, but roughly a factor of ten fewer light sensors (photomultiplier tubes).

A schematic of the first SONGS detector is shown in Figure 3. The detector had a 0.6 ton target mass, 8 photomultiplier tubes reading out the main detector, and 0.5 to 1 meters of water shielding, surrounded by a plastic scintillator cosmic veto.

While unremarkable compared to more expensive state-of-the-art detectors, SONGS demonstrated that a detector of relatively simple design could stably monitor reactor operations, including the burnup effect, for years at a time [8,9,10], and drew the attention of the IAEA and the U.S. and European physics communities.

In 2004, another variant on the reactor monitoring concept was put forth by Hagman and Bernstein [11]. The idea was to make use of the long-predicted but never measured process of coherent scattering of antineutrinos on nuclei [12], a flavor-blind recoil process. The 2004 paper pointed to dual-phase noble liquid detectors as a way to increase the detected rate per unit of mass by a factor of several dozen, depending on the attainable energy threshold in the detector. In 2016, a first-ever measurement of the coherent scattering process with neutrinos was made at the Spallation Neutrino Source at Oak Ridge National Laboratory in Tennessee in the United States [13]. While the neutrino energy is some 10-fold higher than that of reactor antineutrinos, this milestone experiment helps make the case for this alternative detection path in a reactor monitoring context.

In the 30 years after the first demonstration at Rovno, there have been a wide range of theoretical [14,15,16,17,18,19,20,21,22] and experimental [23,24,25,26,27,28,29] efforts around the world to further explore the potential of antineutrino based reactor monitoring, and to develop the technology. These include programs in Brazil, France, Japan, Russia, Taiwan and the United States. The evolution of these efforts is recorded in the agendas and presentations of annual Applied Antineutrino Physics (AAP) Workshops [30].

The IAEA is anticipated to be one of the ultimate users of the technology. Motivated in part by the SONGS results, IAEA examined the utility of the approach in three workshops in 2003, 2008, and 2011. In 2008, while concluding that the then-current state of the technology did not motivate the immediate replacement of existing reactor monitoring techniques, an

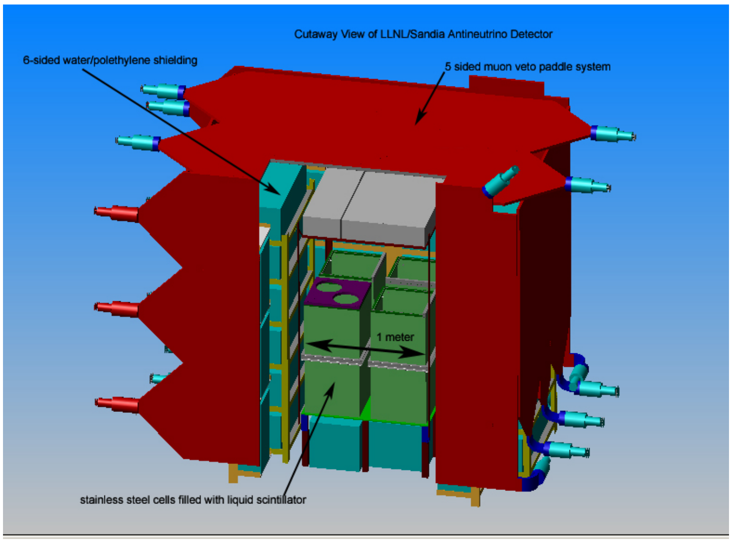

Figure 3 – The SONGS detector.

IAEA expert panel [31] offered these two pertinent recommendations:

1. Above ground deployment will enable a wider set of operational concepts for IAEA and reactor operators, and will likely expand the base of reactors to which this technology can be applied.
2. Provide fully independent measurements of fissile content, through the use of spectral information. This will allow the IAEA to fully confirm declarations with little or no input from reactor operators, purely by analysis of the antineutrino signal.

In 2018, a major breakthrough occurred in neutrino technology of relevance for safeguards, inasmuch as both of the above recommendations of the expert's group were met. PROSPECT, a detector designed to perform a sterile neutrino search at a short standoff from a reactor, demonstrated above-ground spectral sensitivity to reactor antineutrinos [32]. As foretold in the IAEA report, this capability permits a wider range of deployment scenarios, including, for example, an option to deploy a truck-mounted detector that could be driven to a reactor site to accumulate data as part of a safeguards verification campaign.

Fundamental and applied research into neutrinos continue to benefit from each other's successes. Thus, PROSPECT was built not for nonproliferation research but to perform a sterile neutrino search. Similarly, the techniques being developed to measure the coherent scatter process have aided and benefited from technology development related to the search for weakly interacting massive particles, a prime candidate for dark matter. In the latter case, dual-phase noble liquid detectors enjoy the world's leading sensitivity to dark-matter induced nuclear recoils [33,34]. In considering far-field research, such synergy is even more important, because of the scale of the detectors involved.

3 The Far-field

The distinguishing features of far-field monitoring are:

1. Event rates of the order of a few per week or month for the $\sim$50 MWt power reactors of likely interest, even in very large detectors;
2. Electron antineutrino disappearance arising from neutrino oscillaitions must be taken into account;
3. Detector related backgrounds, and real antineutrino backgrounds from other reactors play a more important role compared to the near-field; and,
4. Unlike near-field applications in which there are examples of detection capability down to $\sim$ 50 MWt reactor powers, no antineutrino detectors have been built larger than the 1000 ton KamLAND detector [35], nor neutrino detectors larger than the 50 kiloton Super-Kamiokande [36] detector .

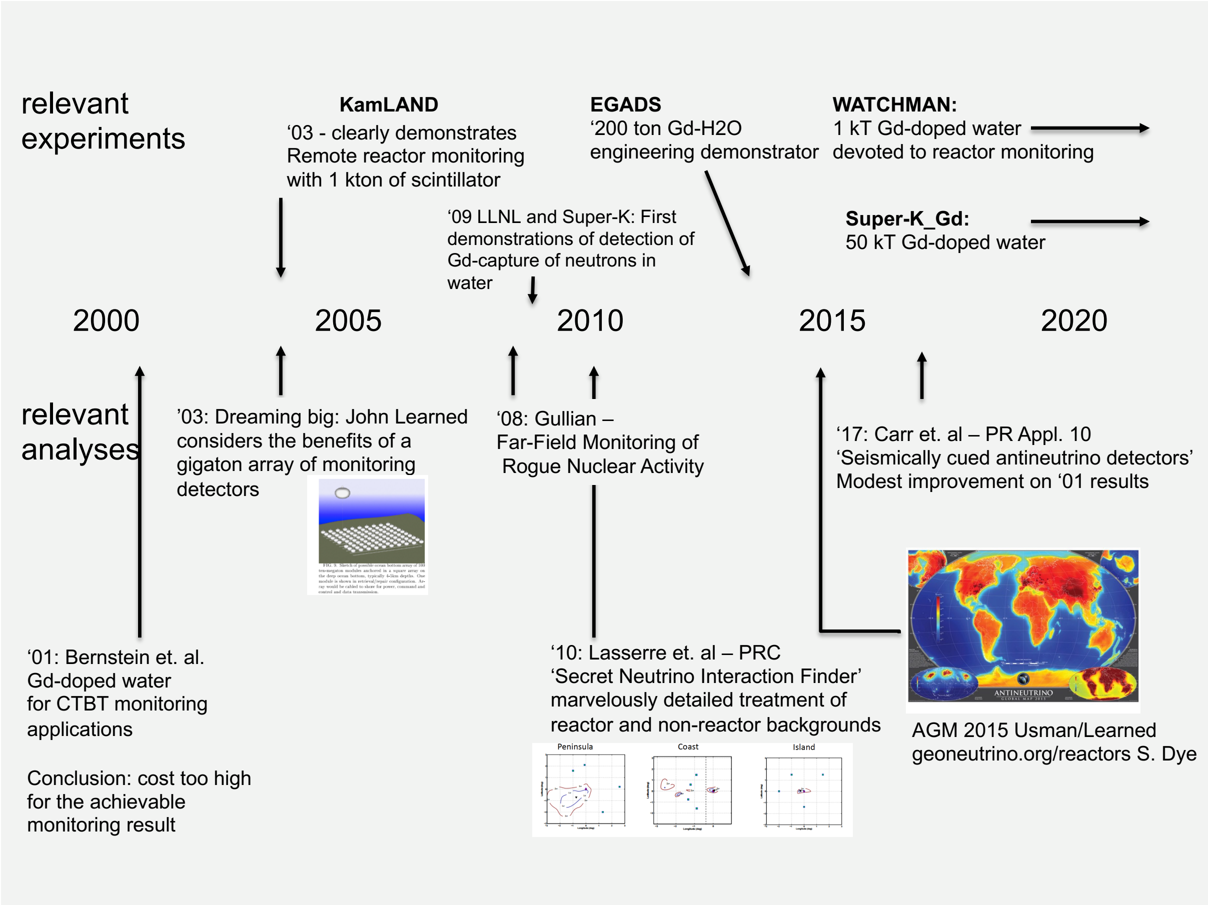

Figure 4 – A chronology of significant events in the history of far-field monitoring.

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One of the first forays into consideration of large antineutrino detectors for nonproliferation [37] examined explosion monitoring for Comprehensive Test-Ban Treaty applications. In this article, the authors concluded that while not ruled out on physical grounds, the practical obstacles to construction of detectors on the scale needed precluded any near-term utility. Nearly twenty years later, a re-examination of the concept in light of the maturation of large neutrino detection technology, and accounting for the possibility of seismic cueing [38], reached a similar conclusion regarding the limited utility for CTBT monitoring.

In the intervening two decades, the more tractable but still daunting prospect of far-field reactor monitoring continued to be explored theoretically. Important theoretical studies included an ambitious thought experiment on gigaton arrays [39], and somewhat more prosaic analyses that offered a more careful and detailed reckoning of backgrounds [40], based on extrapolations from existing large detectors. In 2015, a U.S. government and academic team produced a world map of reactor (and geological) antineutrino emissions [18], taking into account the best understanding of neutrino oscillation parameters, and making use of publicly available data on operating reactors provided by the IAEA [41].

Experimental development of relevant technology was driven by the fundamental science community's interest in low-energy neutrinos to conduct neutrino oscillation measurements. Thus in 2003, the KamLAND experiment had conclusively demonstrated sensitivity to reactors at hundreds of kilometers standoff, using a kiloton-scale scintillator detector [42]. The limitation for far-field applications was that the typical power of the reactors being 'monitored' by KamLAND was on the GigaWatt thermal (GWt) scale, while, as defined earlier, undeclared reactors of the greatest interest for monitoring applications are on the 50 MWt scale.

The CTBT monitoring paper [37] was the first to propose gadolinium-doped water as a medium for measuring reactor antineutrinos via the Inverse Beta Decay (IBD) process. The same idea was also put forward for fundamental physics in 2003 [43], where the motivation was to observe individual supernova with improved efficiency, and to detect the relatively low flux of Diffuse Supernova background [44], generated by all supernova in the history of the universe, and potentially detectable in sufficiently large and low-threshold detectors. In a confluence of need similar to that observed in near-field R&D, members of the Super-Kamiokande collaboration, and a group at Lawrence Livermore National Laboratory each began separate experimental efforts to demonstrate gadolinium-doped water as a neutron detection medium suitable for inverse beta decay Cherenkov detectors. The addition of gadolinium increases the efficiency for neutron which arises from IBD antineutrino interactions on protons in the water. In 2009, the Super-Kamiokande collaboration and the group at LLNL both published results demonstrating first-ever detection of the capture of neutrons on gadolinium [45,46]. The goal of the LLNL group was to develop gadolinium-doped water detectors not for CTBT applications, but for remote reactor monitoring.

Another set of important milestones for the field occurred in the late aughts and early teens of the new millenium. First, the EGADS experiment [47] in Japan showed with a 200 ton engineering demonstration device that the materials comprising a large water detector could be immersed in gadolinium-doped water without degradation of the attenuation length of the water. To achieve the necessary water purity without removing the gadolinium, a customized 'band-pass' filtration method was developed by a group at UC Irvine, in which gadolinium sulfate molecules were selectively removed from the water. The water was then purified by standard means, and the gadolinium compound reintroduced, in a continuous on-line recirculation system. Second, in 2012, a dedicated R&D program was initiated, to work towards a demonstration of remote reactor monitoring, supported by U.S. government nonproliferation research agencies. The WATer CHerenkov Monitor for ANtineutrinos (WATCHMAN) collaboration was formed [48]. The goal of the experimental effort is to demonstrate remote monitoring of the operational status of a single reactor complex using gadolinium-doped water, and to explore techniques to permit increase light collection, enhanced light yield, or other means of increasing sensitivity to the reactor signal. The choice of water was motivated by the significantly longer attenuation length for emitted light compared to scintillator detectors, and the relatively low cost of water as a detection medium. These and other features make water a more likely candidate for scaling to the 100 kiloton or megaton scales needed for remote reactor monitoring. The WATCHMAN team developed a conceptual design for a kiloton-scale demonstration detector comprised of gadolinium doped water, identified a suitable location for the demonstration, and experimentally measured depth-dependent neutron [49] and radionuclide [50] backgrounds that are among the most important limiting backgrounds for a reactor monitoring experiment. In 2018, the collaboration was funded jointly by the US and UK governments to conduct the demonstration at the Boulby underground science facility in Northern England, 25 kilometers distant from the Hartlepool reactor complex. This marks the first dedicated effort to conduct a far-field reactor monitoring demonstration using an antineutrino detector. Also notable in this regard is the decision of the Super-Kamiokande collaboration to upgrade their 50,000 ton pure water detector by adding gadolinium [51]. Though the focus of the experiment is on diffuse supernova and other physics, the gadolinium enhancement will in principle permit sensitivity to Japanese and potentially Korean reactor antineutrino emissions. While not sensitive to the operations of individual reactors, once operational, Super-Kamiokande, with gadolinium added, would become the largest detector in the world with a far-field monitoring capability.

Despite the concerns alluded to above about scaling to megaton class detectors, scintillator-based large-scale detectors are also potentially relevant for reactor monitoring. The current most ambitious scintillator experiment is the 60 kiloton JUNO experiment, which will seek to measure neutrino oscillations and the neutrino mass hierarchy with reactors at approximately 53 km standoff [52]. Scaling beyond this size may be intractable on grounds of expense and attenuation length, but even detectors of this size will have important potential cooperative monitoring applications.

4 Conclusions

Over the last four decades both near-field and far-field applications have enjoyed increased attention from the nonproliferation and physics communities, with significant technological breakthroughs occurring in both areas. This success may be attributed to the natural overlap at the level of technology between the fundamental and applied aspects of neutrino physics, and to the gradual recognition worldwide of the potential convenience and non-intrusiveness of this approach to reactor monitoring. This success and advancement may be viewed as somewhat surprising in consideration of the difficulty of detecting neutrinos, as evidenced by the more than 20 year gap between the postulation of the existence of neutrinos by Pauli, and their discovery by Reines and Cowan. In light of this long arc from theory to practice, a fitting conclusion to this overview comes from Reines himself: "I don't say that the neutrino is going to be a practical thing, but it has been a time-honored pattern that science leads, and then technology comes along, and then, put together, these things make an enormous difference in how we live" [53].

Acknowledgments

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