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Conference Summary

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EXECUTIVE SUMMARY

The XIth workshop on Applied Antineutrino Physics (AAP) held at the Virginia Tech Arlington Research Center from December 7–8, 2015 was attended by more than 50 participants. The AAP workshops are focused on applications of antineutrinos such as non-proliferation or geophysics and generally are attended by a representative cross-section of the relevant communities.

As a result of the continued effort by these communities and the recent interest in sterile neutrinos, several antineutrino detectors, designed explicitly for operation at a distance of several meters to a reactor, are being built or operated worldwide. Applications to the detection of undisclosed nuclear reactors and nuclear explosions are also being investigated. With an eye to this developing technology base, the International Atomic Energy Agency has convened an Working Group to consider applications of antineutrino detectors in current and future safeguards regimes [1].

A major focus of AAP 2015 was the development of prototype detectors for near-field, with a distance of several 10s of meters or less, reactor applications, presented by collaborations based in seven countries. Two preliminary results on the detection of reactor antineutrinos at the Earth’s surface without overburden were presented by the PANDA and T2KEcal collaborations and the Nucifer collaboration showed an unequivocal detection result very close to a reactor. The large number of presentations on actual prototypes and deployments at reactors shows the widespread interest in this field, which has seen a strong increase since 2011, when the reactor antineutrino anomaly was pointed out: in a re-analysis of existing data and re-computation of the reactor antineutrino emissions a 6% deficit in detected antineutrinos from reactors was found. The breadth and depths of these efforts indicate that within the next 12–24 months several prototypes of different designs will demonstrate at-the-surface detection and the ability to measure antineutrino energy spectra. Both are crucial milestones towards applications in near-field reactor monitoring. Several presentations addressed the issue of our understanding of reactor antineutrino fluxes and it is clear that for future applications, precise calibration measurements will be of great benefit.

A number of reports of progress towards the first detection of coherent neutrino nucleus scattering were presented. These efforts greatly benefit from advances in experimental techniques designed for the direct detection of dark matter. Additionally, a first application case for this emerging technology, only possible using this interaction, was presented.

The overlapping spectra of reactor and geoneutrino require that these two communities work closely together. Field of geoneutrinos has made significant progress over the last ten years thanks to the measurements by KamLAND and Borexino. Future experiments will further improve these results and constrain compositional models of the Earth. In particular, global antineutrino maps including both terrestrial and man-made sources of antineutrinos were presented.

The AAP 2015 workshop brought together a diverse and growing community of committed and energetic researchers pursuing a wide range of technologies and theoretical approaches for real-world applications of antineutrino technology. Many of the participants have a background in basic science and this workshop, like all it’s predecessors, clearly showcased the strong synergy between basic and applied science in this field. The recent surge in near-field detector prototypes is attributable to the interest to understand the reactor antineutrino anomaly and the related question of a light sterile neutrino, whose significance for fundamental physics, if it were discovered, can not be underestimated. This interest in sterile neutrinos has also led to an influx of new researchers and ideas into the arena of applied antineutrino physics. In summary, major breakthroughs in antineutrino detection are on the horizon, which will create the the technological base for near-field reactor monitoring.

1 The workshop program and all presentations can be found at http://aap2015.phys.vt.edu/
SUMMARY OF APPLIED GOALS

Nuclear reactors are powerful sources of antineutrinos and this fact has been exploited to study fundamental neutrino properties for more than six decades. At the same time, reactor antineutrinos contain detailed information about the state of the reactor core and its isotopic composition, including the plutonium content, and thus can be used for nuclear non-proliferation and safeguards applications. The highly penetrating nature of antineutrinos makes them impossible to shield and means that detection does not require connection to plant systems or installation within reactor buildings — therefore the antineutrino reactor monitoring technique is highly tamper resistant and non-intrusive. Furthermore, this implies that antineutrino emissions can be detected without time-lag over long distances, allowing, in principle, for long-range verification of the absence of nuclear reactor operations.

The decades of previous neutrino physics experiments using reactor antineutrinos have firmly established a suite of tools and techniques to detect and study these elusive particles. Antineutrinos from nuclear reactors are detected in a hydrogen-rich organic scintillator via the inverse beta-decay (IBD) process:

\[ \bar{\nu}_e + p \rightarrow e^+ + n. \]

The positron deposits its energy promptly in the scintillator, while the neutron thermalizes and is captured by another nucleus. At this point a secondary, or delayed, burst of energy is deposited in the scintillator as the capturing nucleus sheds its excess binding energy. The coincidence between the positron and the neutron capture is a powerful signature of the IBD interaction which makes it possible to separate this relatively rare process from the large background of environmental and cosmogenic activity. Since the positron energy is closely related to the incident antineutrino energy, the IBD process also provides a method for measuring the incident antineutrino energy spectrum.

The application of antineutrino detection to reactor monitoring was first proposed by Borovoi and Mikaelyan in 1978 [2]. In many past reactor experiments a clear correlation between the antineutrino signal and the state of the reactor was found (for early results see [3-5]). Recently, it has been pointed out that a high-efficiency detector with good energy resolution could measure changes in the emitted antineutrino energy spectrum to determine the plutonium content of a reactor in situ [6]. The advantage of reactor antineutrino monitoring is that it does not rely on records of the previous state of the reactor and that it measures directly the operation and isotopic composition of the reactor core which is relevant for its plutonium content.

In this context, a real world application to non-proliferation safeguards will require a detector technology which can operate inside a reactor complex under minimal or without any overburden, in close proximity to a reactor, with minimal shielding and without hazardous liquids [1, 7]. Development of detectors that can operate near the Earth’s surface without cosmic ray attenuating overburden and provide energy spectrum measurements is therefore an important goal for the applied antineutrino physics community. As will be discussed in more detail in the following contributions, similar technology goals are presently being pursued for fundamental neutrino physics studies. With many efforts pursuing a diverse range of technical approaches to these problems, rapid progress is expected.

The application of reactor antineutrinos requires not only detection technology, but also an understanding of reactors as an antineutrino source. Recent results from three very successful experiments (Daya Bay [8], Reno [9], Double Chooz [10]) have shown that reactor antineutrino fluxes and spectra are not as well understood as previously thought. In addition to measuring the
neutrino oscillation mixing angle $\theta_{13}$ these experiments have provided the most precise and detailed measurements of the antineutrino energy spectrum emitted by pressurized water reactors (PWRs). All three measurements used well-calibrated detectors at different reactor sites and observed an unexpected excess of antineutrinos with energies between 4.8 and 7.3 MeV. At present, it is not clear what physics gives rise to the spectral deviation, and therefore additional measurements at different types of reactors that would help to shed light on its origin are a high priority for the neutrino physics field. For safeguards applications, the very same measurements would provide a crucial calibration eliminating the reliance on precise reactor antineutrino flux calculations.

Another application of antineutrino detection technology is the field of geoneutrinos. There is a synergy between the geological community and the applied antineutrino detection community, as their signal is the other’s background. Thus, there is a shared need to understand the nature of both contributions to the neutrino energy spectrum. The dissipation of the Earth’s primordial energy (accretion and core formation) and that from radioactive decay drives plate tectonics and the geodynamo. The question of the mode and rate of heat dissipation and what are the proportions of primordial and radioactive energy driving the Earth’s engine has been a century-old problem. It is now understood that radioactive decay of potassium-40, uranium-238 and thorium-232 is a significant heat source inside the earth. The decay chains of uranium-238 and thorium-232 produce antineutrinos with energies above the inverse beta decay threshold and thus can be detected using current technology $[11,12]$. A precise measurement would improve our understanding of the amount and distribution of the radiogenic heat production in the Earth. The present detectors are all situated on the continents and thus deciphering the relative contributions of the crust and the mantle to the total geoneutrino flux is not achievable at present. This problem is due to the uncertainties in the flux measurement, which is comparable in size to the predicted signal from the mantle, based on all models for the composition of the Earth $[13]$. Moreover, a precise measurement will also provide a critical measure of the planetary Th/U ratio and thus test models of the building blocks for the Earth. The next result in this field will come from the JUNO experiment, where a large background from reactor antineutrinos will need to be subtracted $[14]$. This subtraction will greatly profit from an improved understanding of reactor antineutrino fluxes as would be provided by the experiments discussed in the following.
SUMMARY OF PHYSICS GOALS

Persistent, unproven hints of an eV-scale sterile neutrino have been around since the late 1990’s, when the LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal [13] was shown to be incompatible with the emerging 3-neutrino oscillation framework [16, 17]. Oscillations among the three active flavors have now been confirmed, and this discovery was awarded the 2015 Nobel Prize. The oscillation of active neutrinos is driven by neutrino squared mass differences of less than 0.005 eV$^2$. More recent results [18, 19] and reanalyses of older data [20, 21] can be explained by the existence of eV-scale neutrinos, but no experiment has been able to demonstrate or rule out their existence in the parameter range indicated.

A central role in the tale of eV-scale sterile neutrinos is played by the Reactor Antineutrino Anomaly (RAA): Until the 2011 work by a group from Saclay [22], the results from Refs. [23–25] obtained in the 1980s at the Institut Laue-Langevin in Grenoble were considered the gold standard for understanding antineutrino emissions from reactors. The Saclay group, in preparation of the Double Chooz neutrino experiment [10], revisited the previous results in an attempt to reduce the uncertainties. Instead, they found an upward shift of the central value of the average yield of antineutrinos by about 3% while the error budget remained largely unchanged. This result, in turn, requires a re-interpretation of a large number of previous reactor neutrino experiments, since this changes the expected number of events. Together with the changes of the value of the neutron lifetime [26] and corrections from so-called non-equilibrium effects, previous experiments appear to observe a deficit in neutrino count rate of about 6%; this is called the Reactor Antineutrino Anomaly and was first discussed in Ref. [21]. The initial result on the flux evaluation and the 3% upward shift was independently confirmed in Ref. [27]. In combination this suggests a deficit in the $\bar{\nu}_e$ interaction rate across all reactor neutrino experiments performed to date. At short distances of about 10 m or less, the sterile neutrino hypothesis predicts not only a suppression of the total event rate but also a very specific energy-dependent signature, therefore short-baseline reactor experiments are a crucial test of this hypothesis. A 2012 white paper on light sterile neutrinos [28], signed by nearly 200 authors, summarizes the state of the field and demonstrates the great interest in the underlying physics. Since then, SNOWMASS [29], P5 [30], and the Workshop on the Intermediate Neutrino Program [31] have all identified the eV-scale sterile neutrino as one of the main targets for future small-scale neutrino experiments.

Neutrino mass implies the existence of a right-handed, hence sterile neutrino at some mass scale. The usual seesaw description puts the right-handed neutrino close to the grand unified scale of about $10^{16}$ GeV. While this choice has many attractive features from a model building point of view, there are few phenomenological arguments for this choice or any other scale: the right-handed neutrino being a Standard Model singlet has no associated preferred mass scale and whatever choice is made initially there are no radiative corrections (or non-perturbative Yukawa couplings) which will modify the initially chosen value. As a matter of fact a wide range of masses from sub-eV up to the grand unified scale and beyond are allowed [32]. Discovery of a sterile neutrino would be the first time since the 1970s that a particle not predicted by the Standard Model would be found.

The recent $\theta_{13}$ discovery experiments Daya Bay [8], RENO [9], and Double Chooz [33], along with the earlier generation of reactor experiments at kilometer-scale baselines, CHOOZ [34] and Palo Verde [35], have shown that one can do precision physics with reactor neutrinos in a large detector, located deep underground. In contrast, short-baseline sterile searches must be very close to the reactor which means they will be on the surface and have less space for shielding. The central challenges to any precision short-baseline reactor neutrino experiment are the increased background that comes with the shallow site and the reduced shielding, while maximizing oscillometric sensitivity.
The detection of electron antineutrinos in liquid scintillation detectors is playing a crucial role in exploring neutrino physics and astrophysics, in unveiling the interior of the Earth (i.e. geoneutrinos) and the operation of nuclear reactors. In this framework, on the base of official reactors operational data yearly published by the International Atomic Energy Agency (IAEA), we [36] provide a reference worldwide model for antineutrinos from reactors, discussing the uncertainties on the expected signals. We compiled a comprehensive database of commercial nuclear power plants in the world covering a time lapse of 11 years (2003-2014), which can be freely downloaded from the web page www.fe.infn.it/antineutrino. For each reactor the database reports the relevant operational information such as thermal power, monthly load factors and core type, together with the geographical location. This dataset is a ready-to-use input that everybody can adopt for estimating both the reactor signal and spectra for every location in the world. It is an extremely valuable piece of information for modeling the expected signal at long baseline experiments as they have no close-by reactor that completely dominates the antineutrino flux. We evaluated the expected reactor signal for the KamLAND experiment from 2003 to 2013: the signal time profile is highly affected by the operating conditions of the Japanese nuclear power stations. Indeed, the temporary shutdown of reactors concomitant to strong earthquakes in Japan is clearly visible as a pronounced decrease in the evaluated reactor signal (e.g. Chūetsu earthquake in July 2007 and Tōhoku earthquake in March 2011). As a direct consequence, the discriminating power on the constant geoneutrino signal for the KamLAND experiment also deeply changed in time (see fig. 1).

FIG. 1. Ratio between the reactor signal (R) in the Low Energy Region (LER, 1.806 - 3.3 MeV) and the geoneutrino signal (G) for the KamLAND experiment from January 2003 to December 2013. The two red dashed lines are placed in correspondence to the Chūetsu earthquake (July 2007) and to the Tōhoku earthquake (March 2011).
LIQUID XENON DETECTOR FOR CEνNS. FROM RED-100 TO RED-1000

V. Belov, NRNU MEPhI, for the CEνNS collaboration

A coherent elastic neutrino-nucleus scattering (CEνNS) is a very promising method for detecting reactor anti-neutrinos. The process is allowed by the Standard Model and was predicted theoretically in 1974. Here neutrino interacts coherently with a nucleus as a whole via exchange of a Z-boson. The coherence introduces additional N^2 factor for the cross-section, where N is a number of neutrons in nucleus. There were several proposals through the years for the discovery of this effect. The hard part about it is low energy deposits. Given anti-neutrino energy in MeV scale one ends in keV scale for recoil energy. The fact that it is actually a nuclear recoil results in even lower visible energy. Recent progress in detector technologies in low energy region allowed to introduce a real attempt to find and measure this effect. A COHERENT collaboration was created for that purpose and already began the hunt for neutrinos from SNS at ORNL. We assume that a two-phase emission detector technology is the most suitable for measuring reactor anti-neutrinos. It combines the advantages of gas detectors and the possibility to have the large mass of a target. Main features include a proportional amplification of ionisation signal with the Electroluminescence, a position reconstruction and a wall-less detector construction. But the most promising is its unprecedented sensitivity that goes down to a single ionisation electron. Full power of this technology was demonstrated by the dark-matter search experiments ZeplinIII, LUX and Xenon100. There are several materials that can be used to fill such kind of the detector. In our opinion, a noble gas xenon is the best of those due to the N^2 cross-section boost and the high density. It has no long-living cosmogenic activation isotopes what is important for ground operation. The charge yield for nuclear recoils in liquid xenon was well measured recently and found to be almost constant at the level of 7-8 electrons/keV at 1 keV region. The disadvantage of xenon is a relatively high market price of 3$/g. Nevertheless liquid xenon is used in various detectors for many years. There is a very well developed technology for purification of xenon. The new coming experiments Xenon1T, LZ and nEXO will provide experience of operation of a ton scale liquid xenon detectors. Thus we propose a two-phase xenon emission detector with 1000 kg of liquid xenon in active region. It will use a novel CEνNS for detection of reactor anti-neutrinos. Principal design follows the scaled up already operated detectors like LUX or RED-100. Thanks to the high density of liquid xenon the target can fit a cryostat 120cm in diameter. This allows one to fit it inside a shipping container with reasonable 100cm shield of Fe and plastic. All other systems for the detector (cooling, gas storage and purification, electronics) can fit the same container with big aim to require only electric power from outside for a long-term operation. Expected cross-section for CEνNS is 700 times larger than that for an inverse beta decay on proton (IBD). Our calculations show that at 20m distance from 3 GWth power reactor core one could have 0.4Hz of registered neutrino events in the detector. With this scale of count rate the reaction time for a sudden stop of the reactor is of an order of 5 minutes. The count rate reaches a unique level of 35k events/day. This is enough for daily monitoring of reactor power with statistical accuracy 0.5%. For a period of 10 days, the statistical uncertainty goes down to 0.17%. That is close to the expected decrease in count rate 0.2% coming from fuel composition change due to its burn-up. At the same conditions a 1-ton IBD detectors can see only several thousands of events/day what is 10 times smaller.
Projects focused on Short Baseline Neutrino Physics (SBL), in particular those with the primary goal of resolving the flux and spectral “reactor anomalies,” have become a major focus of this workshop. This is natural given the considerable, but imperfect, overlap with Reactor Monitoring R&D, i.e. efforts whose primary goal is development and demonstration of technology for monitoring applications. Here we examine similarities and differences to provide background for AAP participants whose focus is mostly on a single of these topics and to generate discussion within the AAP community on where boundaries fall and whether there are synergies that can be further developed. We will explore this topic through comparison of central features of each endeavour. This is not an exhaustive list and identification and consideration of other features is to be encouraged.

**Detector Performance:** The requirements for SBL, as determined by the physics goals of these experiments, are in general near-surface operation with S:B > 1, energy resolution better than the recent $\theta_{13}$ experiments, efficiency > 10%, and a precision energy scale understanding. These stringent requirements would provide any presently envisioned RxM capability. Particular RxM applications guide the level of performance required which can span a range from simple counting to precision spectral measurements.

**Deployment Location:** Both SBL and RxM oriented devices must be non-intrusive, since there is a very limited likelihood of host site reconfiguration or dedicated construction. SBL efforts have a strong preferences for $^{235}\text{U}$ fueled research reactors and a requirement for the shortest practical baseline. For RxM efforts the reactor type is determined by the application and there is no firm constraint on baseline (although closer is better for higher flux). That is, SBL efforts prefer sites with more challenging characteristics.

**Scale of the Field:** Detectors built for SBL efforts will be “bespoke,” tailored to the physics goals. To date, this is also true for RxM devices, but the path to widespread use should also be considered. The range of approaches being pursued in both fields will be an advantage when responding to requirements for a particular RxM application.

**Mode of Operation:** The monitoring & calibration intensity of a typical physics experiment is incompatible with non-intrusive operation & personnel resources for RxM. SBL efforts will doubtless work towards unattended operation, balancing this desirable feature against precision physics goals, thus providing an excellent test case in this regard.

**Host Site Collaboration:** RxM demonstrations and SBL are similar: the host site is likely to be a collaborator from which logistical support and reactor data is obtained. This relationship is likely to be different than any experienced by the AAP community to date in RxM applications, where collaboration and detailed information sharing cannot be assumed.

**Conclusions:** It is evident that RxM and SBL have many similarities, as well as important differences. SBL efforts will provide important capability demonstrations and data, including a detailed understanding of near-surface background and performance of mitigation strategies and an improved understanding of reactor antineutrino emissions, that will inform what is possible for RxM applications. The diverse technological approaches of the community are a strength: we will learn a great deal from careful comparisons of performance, and a single approach is unlikely to be optimal for all RxM applications.
The Double Chooz reactor antineutrino experiment aims for a precision measurement of the neutrino mixing angle $\theta_{13}$ via the disappearance of reactor $\bar{\nu}_e$. Antineutrino are detected by inverse beta decay on free protons in a 8.3 tons liquid scintillator target doped with Gadolinium. Double Chooz is located in France, near the Chooz nuclear power plant. The far detector is 1050 m away from the two pressurized water reactor cores, each delivering 4.25 GW thermal power. A second identical detector, located at an average distance of 400 m from the two reactor cores has been commissioned and is now operating since one year.

Due to the one-detector configuration up to 2015, the collaboration had to develop novel analysis techniques like reactor rate modulation study which gives independent measurement of $\theta_{13}$ and background rate, new efficient background veto techniques or analysis using neutron capture on Hydrogen with independent data sample. Using far detector only data, the latest Gd result is $\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$[37] and the new Hydrogen analysis yields to $\sin^2(2\theta_{13}) = 0.124^{+0.030}_{-0.039}$[38] and demonstrates the capability of precise measurement of reactor $\bar{\nu}_e$ without Gd loading (cf. Fig. 2).

Additionally to the main analysis, the Double Chooz collaboration has provided several side analysis interesting in the field of antineutrino applied physics. The directionality analysis has proved the capability of the detector to measure the neutrino source direction by the inverse beta decay process with both Gd and Hydrogen neutron captures. Using the periods were only one reactor was running the sensitivity to each core direction was also demonstrated[39]. The orthopositronium (o-Ps) formation has been observed, using a pulse shape analysis on an event by event basis[40]. Such effect could be very interesting to distinguish signal from cosmogenic background but will need further technological developments to increase the o-Ps formation fraction.

With the near detector now running, exiting results are expected for the main analysis with a $\sigma$ of the order of 0.01 on the $\theta_{13}$ value. The near detector will also provide more statistics and a better sensitivity to distinguish each reactor for the directionality studies.
DETECTION OF BREEDING BLANKETS USING ANTINEUTRINOS
B. Cogswell, Program on Science and Global Security, Princeton University

The Plutonium Management and Disposition Agreement between the United States and Russia makes arrangements for the disposal of 34 metric tons of excess weapon-grade plutonium. Under this agreement Russia plans to dispose of its excess stocks by processing the plutonium into fuel for fast breeder reactors. To meet the disposition requirements this fuel would be burned while the fast reactors are run as burners, i.e., without a natural uranium blanket that can be used to breed plutonium surrounding the core. This talk discusses the potential application of antineutrino monitoring to the verification of the presence or absence of a breeding blanket. It is found that a 36 kg antineutrino detector, exploiting coherent elastic neutrino-nucleus scattering and made of silicon, could determine the presence of a breeding blanket at a liquid sodium cooled fast reactor at the 95% confidence level within 90 days. Such a detector would be a novel non-intrusive verification tool and could present a first application of coherent elastic neutrino-nucleus scattering to a real-world challenge.
RICOCHET

J. A. Formaggio, Massachusetts Institute of Technology, Cambridge, MA, USA, for the Ricochet Collaboration

The Ricochet experiment is a nascent endeavor aimed at detecting neutrinos by using the yet-to-be-observed coherent elastic neutrino-nucleus scattering (CENNS) process. This predicted mode of observing neutrinos opens a myriad of scientific possibilities to neutrino physicists, such as searching for additional species of neutrinos, understanding supernovae, and nuclear reactor monitoring. The channel remains unobserved to this day due to the fact that such interactions deposit extremely small recoil energies. Fortunately, cryogenic detector technologies have advanced sufficiently to place a first CENNS detection within reach.

To observe these interactions, the Ricochet program focuses on thermal cryogenic detectors which are specialized to achieve extremely low recoil energy thresholds. The requirements for such a detector are very challenging, since the recoil energy deposited by these interactions is extremely small (tens of eV). Our proposal uniquely focuses the detection mechanism on measuring the phonons created in the interaction. Thermal phonons sample the full energy of the recoil with no quenching effects. Detailed studies of the phonon process involved in such detectors reveal that, with proper optimization, recoil thresholds as low as 10 eV can in principle be achieved. Our first detector concept used conventional dielectric materials, such as silicon and germanium (Phys. Rev. D85, 013009 (2012)). Since then we have explored the idea of using metallic superconductors as a detector target material. Superconducting metals should be almost completely insensitive to the dominant background in these experiments (electromagnetic) while being very sensitive to neutrino interactions (recoils); as quasi-particle production that accompanies electromagnetic interactions are strongly quenched in superconducting metals, while phonon production is not. If experimentally verified, such a feature would place these superconducting detectors at a distinct advantage over other conventional recoil detectors in their ability to reject unwanted backgrounds.

The first tests of such detectors will take place at the MIT Research Reactor. Measurements of the environmental backgrounds at the site (when the reactor is on and off) have commenced. A small few-kg target will be deployed over the next two years to test the concept of the detection technology to determine its feasibility as well as its scalability. If successful, the Ricochet technique could be expanded to provide monitoring of nuclear reactors, in particular portions of the neutrino flux that fall below the typical energy threshold of conventional (inverse beta decay) techniques.
Coherent neutrino-nucleus scattering represents a new and unique window for physics beyond the standard model. The cross-section for the process is greatly enhanced by the coherent nature of the reaction. The CONNIE experiment has the goal of detecting coherent neutrino-nucleus interactions using low threshold Charge Couple Devices (CCDs). The relatively low mass of the silicon nucleus, as well as the low readout noise, make CCDs an ideal instrument for the identification of the nuclear recoils with keV-scale energies. These recoils are expected from neutrino nucleus coherent scattering. Historically, CCDs have not been considered as a viable nuclear recoil detector due to their relatively low active mass. Yet, recent advances in CCD technology, mostly due to the increase in the purity of the silicon, allow for the fabrication of up to sensors with up to 6 g of active mass, with exceptionally low levels of radioactive contamination. R&D efforts to produce 20 g sensors are underway. These instruments have been successfully characterized and deployed in astronomy experiments \cite{41} and in experiments searching for dark matter citeChavarria:2014ika. The low energy threshold of CCDs provides a unique opportunity to detect the neutrino-nucleus coherent scattering \cite{3}, and the CONNIE Collaboration is investigating this possibility. The CONNIE prototype was installed at the Angra-2 Nuclear power plant in Brazil during September-October 2014. It has been running with engineering detectors since December 2014 with a total active mass of 8 g. The detector is running inside a conditioned shipping container installed at a distance of 30m from the core of the 4GW nuclear reactor. The operation of the experiment is based at Centro Brasileiro de Pesquisas Físicas (Rio de Janeiro, Brazil). The full shield was completed in July-August 2015. The CONNIE Collaboration in planning an upgrade to a detector with 100 g of active mass in Summer 2016. As discussed in \cite{42}, with a background 600 events/kg/day/keV a 3 sigma detection significant of the SM coherent scattering is expected in 36 days of running. The current background achieved at the reactor site with partial shielding is ~6000 events/kg/day/keV, giving a 3 sigma detection in one year. We believe this is a conservative estimation because we expect an improvement in the background level when the full shield is assembled.

The success of the installation and run of the CONNIE prototype, has demonstrated the feasibility of operating a CCD array at the Angra-2 nuclear power plant as a detector for coherent neutrino scattering. The results of the engineering run will be published early in 2016. The planned upgrade to 100 g will reach sensitivity for the standard model process, and probe interesting new physics in the low energy neutrino sector \cite{43}. 
ONLINE MONITORING OF THE OSIRIS REACTOR WITH THE NUCIFER NEUTRINO DETECTOR

J. Gaffiot, CEA Centre de Saclay, IRFU - Service de Physique des Particules, for the Nucifer collaboration

Nucifer is a new reactor neutrino detector designed for non-proliferation, focusing on simplicity and reliability using industrial components. Neutrino counting is done through the inverse beta decay reaction on free protons in about 850 L of gadolinium doped liquid scintillator, loaded in one single tank and surveyed by 16 photomultiplier tubes. The tank is surrounded by a plastic scintillator muon veto and passive shieldings to handle backgrounds, as depicted on figure 3.

Nucifer has been deployed only 7.2 m away from the Osiris research reactor core (70 MW), operating at the Saclay research center of the French Alternative Energies and Atomic Energy Commission (CEA). The detector successfully worked remotely operating at a shallow depth equivalent to $\sim 12$ m of water and under intense background radiation conditions due to the very short baseline. Based on 145 (106) days of good quality data with reactor ON (OFF), a mean rate of $281 \pm 7 \bar{v}/\text{day}$ has been measured, to be compared with the prediction of $280 \pm 23 \bar{v}/\text{day}$, with a detection efficiency of 30.3%. The main systematic is the uncertainty on efficiency, due to the energy scale calibration. It is worth noting that the reactor off correlated background showed significant variations correlated with the atmospheric pressure which are corrected thanks to the online measurement of the muon flux.

The Osiris neutrino flux variation is less than 1% during a cycle, and is thus impossible to detect with Nucifer. So, as a potential application, we decided to study the possibility to safeguards the burning of highly enriched plutonium fuel with neutrinos. Nucifer would be capable to separate a standard Osiris core from a core where 1.55 kg of $^{239}$Pu replaces $^{235}$U at 95% C.L., both core operating at the same thermal power.

The Osiris reactor has definitively been shut down on December 16th 2015, and the collaboration is studying the deployment of Nucifer nearby a nuclear power station. At a few 10 m from the core, the detector would be almost free of accidental background, even without passive shielding, and the sensitivity would be enhanced.

FIG. 3. Cut view of the Nucifer detector. The overall footprint is about $3 \times 3 \text{m}^2$. 

1. Stainless steel tank
   Teflon coated
2. Nitrogen atmosphere
3. 16 PMTs
4. Acrylic buffer
5. Target Liquid (0.8 m$^3$)
6. Calibration tube
7. Cosmic ray veto
8. 15 cm B-doped polyethylene
9. 10 cm Lead
The COHERENT Collaboration seeks to make an unambiguous observation of the coherent elastic neutrino-nucleus scattering (CE$\nu$NS) process using a suite of three highly-sensitive detector systems at the Spallation Neutron Source (SNS) of Oak Ridge National Laboratory. The detectors proposed to comprise the COHERENT effort are a 14.6-kg CsI$[\text{Na}]$ crystal scintillator, 15-kg of germanium P-type point contact detectors, and a dual-phase liquid Xenon (LXe) time-projection chamber.

Stopped-pion neutrino beams, such as the SNS, have been previously been recognized as attractive options for CE$\nu$NS searches. The neutrinos produced by the 60-Hz SNS proton beam, fully contained within 700 ns, consist of two populations with distinct energy and timing characteristics: prompt neutrinos, originating from the decay of pions produced in the spallation process, are nearly mono-energetic at 29.9 MeV and are tightly correlated with the beam; the delayed neutrino population is produced by muon decay ($\tau = 2.2 \mu s$) and has neutrino energies up to approximately 50 MeV; figure 4(a) shows the nuclear recoil spectrum in the COHERENT detectors for SNS neutrinos.

In addition to the observation of the CE$\nu$NS process, COHERENT will carry out independent, high-precision characterizations of quenching factors (QFs) or detector response for low-energy nuclear recoils and perform measurements of the cross sections for production of neutrino-induced neutrons (NINs) on various targets, initially including lead and iron. NINs are a unique background for the COHERENT experiment, with contributions possible from both neutral- and charged-current interactions, and the process is thought to be involved in nucleosynthesis in addition to being the mechanism by which the HALO supernova neutrino observatory will work.

The anticipated statistical significance of CE$\nu$NS observation for COHERENT is shown in Fig. 4(b). CE$\nu$NS data is already being collected by the CsI$[\text{Na}]$ detector at the SNS and an extensive background-measurement campaign is underway. Relocation of the Xe detector, RED-100, to the SNS is expected by mid-2016, and an agreement is in place for loan of the MAJORANA Demonstrator prototype module for the COHERENT effort.

**FIG. 4.** (a) Nuclear recoil spectra for CE$\nu$NS interactions at the SNS for the three detector media to be deployed by COHERENT. Recoils associated with the prompt and delayed neutrino populations are shown. (b) Anticipated statistical significance of CE$\nu$NS observation by the COHERENT detectors.
CHANDLER DETECTOR NEUTRONICS MODELING

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The CHANDLER anti-neutrino detector consists of $16 \times 16 \times 16$ cubes of plastic scintillator, sandwiched between 17 thin sheets of Li-6-loaded neutron absorbing scintillator. The anti-neutrinos are detected by the inverse-beta-decay (IBD) reaction in the scintillator. Charged particles will deposit their energy in the plastic scintillator while a neutron signature is generated by absorption in the neutron detector sheets. A major source of background noise is cosmogenic fast neutrons. These can scatter from the hydrogen to create a recoil proton and then be absorbed in a neutron detector sheet. This process can “look” like an IBD event because it creates a charged particle and neutron with a similar time-coincidence. If the rate of these cosmogenic fast neutron events is high, then a good method to discriminate them will be required. To study this issue, the current of cosmogenic neutrons was calculated using the MCNP6 code with a full atmosphere model and cosmic proton/alpha source. The total neutron current at sea level was calculated to be $37.8 \text{ n}/(\text{m}^2 \text{ s})$ ($\pm 3\%$) with an average energy of 107 MeV. Our preliminary studies indicate that with 1-meter of high density polyethylene shielding, the cosmogenic neutron current can be reduced by 98%. With shielding, CHANDLER would be exposed to 64,000 neutrons/day, compared to only 500 IBD events/day. This reduced neutron current was then simulated impinging on the detector, and any neutron that resulted in a neutron-proton pair being absorbed in the detector was recorded. The space and time-coincidence of these events are shown in Fig. 5. Most of the neutrons generated from IBD events are absorbed in the same cube as they were created due to their low energy, whereas the high-energy cosmic neutrons tend to travel further. Further, the energy of the proton for cosmic neutrons is typically much higher. The time-correlation between the two sources of neutrons are similar. By limiting signals by their charged particle energy (less than 20 MeV) and their space-coincidence (up to one cube away), then most of the IBD signal is kept (80%), while the cosmic neutron signal is reduced by approximately three orders of magnitude to give a signal-to-noise ratio of 10. If a higher SNR is required, then more shielding could be used. Future studies should address development of a multi-layered shield with a low mass that can effectively remove different particles.
PROSPECT – A PRECISION REACTOR OSCILLATION AND SPECTRUM EXPERIMENT

Karsten Heeger, Yale University, Department of Physics, Wright Laboratory, New Haven, CT, USA, for the PROSPECT collaboration

The Precision Reactor Oscillation and Spectrum Experiment (PROSPECT) [51, 52] at the High Flux Isotope Reactor (HFIR) [53] at Oak Ridge National Laboratory (ORNL) is designed to make a high-precision measurement of the antineutrino spectrum from $^{235}$U at a research reactor with a highly-enriched uranium (HEU) core and to search for short-baseline neutrino oscillation at distances of <10 m from the reactor as a signature of eV-scale sterile neutrinos. A measurement of the relative flux and spectrum of $\bar{\nu}_e$ over a range of distances from the core will allow PROSPECT to probe the allowed parameter space for sterile neutrino oscillation suggested by the reactor anomaly and radioactive source experiments [28]. PROSPECT’s precise spectrum measurement of a HEU reactor will inform the modeling of reactor $\bar{\nu}_e$ production and help understand the spectral deviations observed in recent $\theta_{13}$ experiments [54]. It will improve reactor monitoring capabilities for nonproliferation and safeguards and complement decay heat measurements for reactor design and safety. The reactor anomaly and spectral deviations are open issues in a suite of anomalous neutrino results that may hint at revolutionary new physics in the neutrino sector. PROSPECT is a novel short-baseline reactor experiment with discovery potential for fundamental physics and applications in neutron detection and reactor monitoring [55].

PROSPECT is conceived as a phased experiment using two segmented antineutrino detectors at distances of $\sim$7-19 m from the HFIR reactor core. See Fig. 6. Antineutrinos are detected through the inverse beta-decay reaction. The segmented detector design enables the measurement of the $\bar{\nu}_e$ rate and spectrum as a function of distance from the reactor core. Phase I consists of a 3-ton, $^6$Li-doped segmented liquid scintillator detector optimized for good neutron detection and efficient background rejection through pulse shape discrimination, fiducialization, and topological event identification. With 120 individual, optically-separated detector units with double-ended 5”-PMT readout, the Phase I detector is designed to minimize the amount of non-active detector material and yields an energy resolution of $\sim 4\%/\sqrt{E}$. The Phase I detector is movable over a distance of 7-12 m from the reactor for increased baseline coverage and sensitivity in the oscillation search and systematic cross-checks and background studies. The active detector is housed inside layered passive shielding to suppress reactor and environmental backgrounds [56]. In Phase II, a second, stationary 10-ton detector placed at 15-19 m from the reactor provides additional target mass and increased oscillation sensitivity. In Phase I PROSPECT will detect $\sim$700 $\bar{\nu}_e$/day with a signal to background ratio of >1:1. With 1 year of Phase I data, PROSPECT will test the best fit of the sterile neutrino hypothesis at $>4\sigma$. PROSPECT will probe the favored region at $>3\sigma$ with 3 years of Phase I data and the allowed region at $>5\sigma$ with 3+3 years of data taking in Phase I+II [55].

FIG. 6. Left: Layout of the PROSPECT detectors AD I and AD II at HFIR, ORNL. Center: Segmented active detector design with 25-l detector units. Right: PROSPECT sensitivity to 3+1 neutrino oscillations.
Large gadolinium-doped water Cherenkov detectors are currently being investigated for the use in long range remote monitoring of nuclear reactors. At the kiloton scale, these detectors would be capable of excluding the existence of an operating 10 MWt reactor in a ~25 km radius and could therefore be utilized to non-intrusively confirm the non-operation of declared and/or clandestine reactors within this radius. At the megaton scale, the radius could potentially be extended to several hundreds of kilometers, possibly enabling cross-border monitoring. Over such large sensitive areas, the likelihood of detecting antineutrinos from multiple independent reactor facilities increases. However, if the detector is able to determine the direction of the incident antineutrinos, reactor discrimination may be possible. Furthermore, because antineutrinos are seldom produced in such high quantities anywhere apart from nuclear reactors, directionality could possibly enable the ability to search for and locate clandestine reactors within the sensitive radius of the detector. Directionality can also be utilized to enhance experiments within the physics community such as neutrino oscillation and supernova detection.

The primary detection method in Gd-doped water Cherenkov detectors is the coincident detection of the resultant positron and neutron from the inverse beta decay (IBD) interaction. While this interaction allows for a good determination of the incident antineutrino energy, it is difficult to extract directional information from IBD in water detectors due to the low sensitivity and spatial resolution. The goal of this work was to determine whether an alternative interaction, elastic antineutrino-electron scattering, can be utilized for this purpose. The directions of scattered electrons are highly correlated with the incident antineutrino direction and thus the initial antineutrino direction can be statistically determined from an ensemble of scattering events. Electron scattering poses a challenge however, due to its smaller cross-section and larger background compared to IBD (singles vs. coincident detection). Using the proposed kiloton WATCHMAN detector as a baseline model, our work included a detailed investigation into the expected electron scattering signal and various sources of background, including solar neutrinos, misidentified reactor-based IBD events, the decays of cosmogenic radionuclides and water-borne radon, and gamma rays from the photomultiplier tubes, detector walls, and surrounding rock. Our results so far indicate that directional sensitivity may be achievable in a kiloton sized detector approximately 10 km away from a commercial power reactor on the timescale of five years if the following conditions are met: use of low background photomultiplier tubes and sufficient fiducialization, large overburden, and significant improvements in radon contamination control in water. The last condition may be the most difficult to achieve in practice, since reductions on the order of 100 to 10,000 times that of recent detectors is currently required for directional sensitivity.
ANTINEUTRINOS FROM NEUTRON CAPTURE

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Nuclear reactors are the largest terrestrial source of antineutrinos. The process of fission produces multiple fission fragments, which beta-decay to stability, releasing antineutrinos. This direct relation between fission rates, or macroscopic fission cross-section multiplied by the neutron flux $\Sigma_{\text{fiss}} \phi$ and antineutrino rates $\Gamma_\nu$, means that $\Gamma_\nu \propto \phi$ for the vast majority of nuclides in a reactor. This forms the backbone of current rate estimates. However, there is a correction to the overall antineutrino spectrum stemming from non-linear nuclides, antineutrinos from neutron capture. This correction, similar in signal shape to the spent fuel \cite{57} and non-equilibrium \cite{22} corrections, arises from antineutrino-producing nuclides that are only generated from neutron capture.

The non-linear correction results in a low-energy excess of antineutrinos, which do not appear in the original Schreckenbach measurements \cite{21, 25} nor the new Haag measurement \cite{58}, as shown in Fig. 7. This fact makes a quantification of the non-linear effect necessary, accomplished by the authors in Ref. \cite{59}. A full understanding of the non-linear correction, along with other corrections, will supply a more accurate source determination to the applied antineutrino physics community. This is critical to sterile neutrino searches and reactor monitoring, both being presented at the AAP2015 meeting.

Four major nuclides were identified as non-linear: $^{100}$Tc, $^{104}$Rh, $^{110}$Ag, and $^{142}$Pr. An analytical evaluation revealed an antineutrino rate: $\Gamma_{\text{nonlinear}} \propto T_{\text{irr}} \phi^2$. Detailed reactor simulations using the SCALE \cite{60} suite confirmed this relation and it was found that commercial reactors can experience up to a $\sim 1\%$ non-linear correction. Magnox (5 MW$_e$) and heavy-water (IR40) reactors have a lower correction. Research reactors (IRT and HFIR) also have small non-linear contributions, as long as they are run with low irradiation times. Finally, the Schreckenbach measurements conducted at the ILL research reactor are safe from any non-linear contamination.

In conclusion, our work in Ref. \cite{59}, identifies and quantifies another low-energy correction for the reactor antineutrino spectrum. This provides a more accurate source model for short-baseline experiments utilizing a single detector and reinforces the need for detailed reactor simulations to fully understand the reactor as an antineutrino source.
THE POTENTIAL TO RESOLVE SPECTRAL ANOMALIES WITH DIFFERENT REACTOR EXPERIMENTS

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Recent reactor experiments at km-baselines succeeded to measure the parameter $\theta_{13}$, the smallest of the three known weak mixing angles. With these experiments, major progress has been made with respect to energy resolution as well as energy scale systematics. A measurement of the reactor antineutrino spectra with high precision became possible, which show an unexpected excess of events at about 5 MeV visible energy relative to the spectrum predictions. The excess translates into a shoulder in the neutrino spectrum at 5-7 MeV or a "bump" in the ratio of measured and predicted spectra. This spectral anomaly is observed in comparison to the reactor spectra obtained from a conversion of beta-spectrum measurements to neutrino spectra. In contrast to this, spectrum predictions summing up each of the individual decay branches using nuclear databases can yield similar spectral structures as seen by the measurements. An interpretation of the "summation spectra", however, is associated with large systematic uncertainties, owing to missing data or discrepancies between different databases. A novel approach is to combine the antineutrino spectrum measurements of different reactor types [61]. Comparing the spectra measured at a LEU (Low Enriched Uranium) commercial reactor and a HEU (Highly Enriched Uranium) core, the following three hypotheses can be tested: the excess is created (1) by all fissioning actinides at same strength, (2) by $^{235}$U only, or (3) by any actinide but $^{235}$U. Figure 8 shows as an example the event ratio of the projected data for the Stereo (HEU) and Double Chooz near detector (LEU) after two years of data taking. The computations are based on the Huber-Haag reference spectra, the error bars are statistical and include the model uncertainty of the Huber-Haag spectra taking into account correlations between the different isotopes. The detector response is not included in this plot. The lines are obtained from a polynomial fit to the Huber-Haag spectra.

FIG. 8. Event ratio of HEU to LEU antineutrino spectra for three hypotheses. Data points show the event ratio of the projected data for Stereo (HEU) and Double Chooz near detector (LEU) using the Huber-Haag spectra for two years of data taking. The errors are statistical and include the model uncertainty of the Huber-Haag spectra taking into account correlations between the different isotopes. The detector response is not included in this plot. The lines are obtained from a polynomial fit to the Huber-Haag spectra.
The Stereo detector has been designed to achieve a high sensitivity to the shape of the energy spectrum of electronic antineutrinos ($\bar{\nu}_e$) emitted by reactors within a modest target volume of 2 m$^3$. Its main motivation is to look for a new oscillation pattern at short baseline from the compact reactor of ILL (Grenoble, France). Such pattern would be the signature of a sterile neutrino of mass around 1 eV, mixing with the reactor $\bar{\nu}_e$'s. The detection technology is based on the interaction of the $\bar{\nu}_e$ flux in a liquid scintillator (LS) doped with gadolinium via the Inverse Beta Decay process. This technique has been developed and validated by several reactor experiments and shows the highest sensitivity in published results so far. The target volume is divided into six identical cells of dimensions $900 \times 900 \times 375$ mm$^3$, optically isolated from each other. In order to guarantee a homogeneous response in the whole volume of a cell a highly reflective layer made of VM2000 foil coupled up to an air gap coats the internal surface and the scintillation light is collected by four PMTs on the top of each cell separated from the LS surface by a thick acrylic buffer (see fig. 9). About 350 photo-electrons per MeV are expected on average. Several systems will allow to circulate sources underneath, around and inside the detector to fully calibrate and monitor the detector response. The real challenge of Stereo is the mitigation of the background while operating at 10 m only from the core of the reactor and close to surface. Several campaigns of measurements have been performed to characterize all sources of background. A set of online rejection techniques are implemented including the pulse shape discrimination of the LS, a 30 cm thick crown around the target filled with undoped LS to veto the external background, and a muon veto above the detector. These techniques are complemented by an extensive use of passive shielding. In particular the detector is installed underneath a large water channel (6 m thick) reducing the cosmic-ray induced background, ultimate limitation on the sensitivity. Most parts of the detector are currently under fabrication. Stereo should be assembled on site in spring-summer 2016. The expected $\bar{\nu}_e$ rate is 400 per day with a signal/background ratio of 1.5, allowing to cover the reactor anomaly contour after 1.5 year of data taking with 95 % C.L. Thanks to the good control of the detector response, Stereo should provide a reference measurement of a pure $^{235}$U fission neutrino spectrum since the ILL reactor burns a highly enriched fuel. Such spectrum is of great interest for applications to the surveillance of reactors and for upcoming high precision reactor experiments (see J. Haser’s contribution).
CHANDLER stands for Carbon Hydrogen Anti-Neutrino Detector with a Lithium Enhanced Raghavan-optical-lattice technology developed at Virginia Tech. The CHANDLER technology combines the best aspects of the SoLid reactor detector design [62] (efficient, low-background neutron tag, and high spatial resolution) with the optical lattice readout scheme originally proposed by Raghavan [63]. This combination results in excellent energy resolution and improved neutron tagging efficiency, while maintaining the high spatial resolution that is critical to reducing the random coincident and fast neutron backgrounds that could otherwise swamp the IBD signal at an above ground location, very near to an operating reactor. The detector is configured as alternating layers of wavelength-shifting plastic scintillator [64] cubes and $^6\text{LiF}:\text{ZnS(Ag)}$ neutron detection sheets [65]. In an IBD interaction, the primary light from the positron is created almost exclusively in the scintillating cubes ($\tau \sim 9 \text{ ns}$), while approximately 70% of the neutrons are captured on the $^6\text{Li}$ in the sheets producing a slow-release ($\tau \sim 200 \text{ ns}$) light pulse in the ZnS(Ag) scintillator that is unique to neutron capture. The light produced in the sheets is absorbed and retransmitted by the wavelength shifter in the cubes and can then be transported, along with the primary light produced in the cubes, by total internal reflection along the four cube row and column directions that run parallel to the sheets. In this way the exact location of the primary positron and secondary neutron capture are known with the precision of the cube dimensions ($62 \times 62 \times 62 \text{ mm}^3$). At the edge of the detector, each row and column of 16 cubes is readout by a 2 inches photomultiplier tube (PMT) connected to a charge-integrating, pulse-shaping amplifier with a 25 ns shaping time readout by a CAEN 12-bit, 16 ns waveform digitizer. The detector concept proposed here is an evolution of the SoLid design [62] which increases the energy resolution from about 14% to 6% at 1 MeV. This improved design, referred to as SoLid*, achieves its improved energy resolution by increasing the light collection, while maintaining the tight spatial resolution of SoLid. The SoLid collaboration has 10 member institutions in the UK, Belgium, France and the U.S. with a total membership of about 50. The SoLid collaboration will build and deploy a 2 tons of detector by the end of 2017 and then will run with the SoLid detector for 3 calendar years or $\sim 450$ equivalent full power days. The resulting sterile oscillation sensitivity is shown in Fig. 10. The SoLid* detector will be installed at the shortest baseline to take advantage of the superior resolution in $L/E$ and maximize sensitivity on the high $\Delta m^2$ side. The longer SoLid detector will be installed behind SoLid* to maximize coverage in $L$ and extend the sensitivity in lower the $\Delta m^2$ region.

**FIG. 10.** Sensitivity results at $3\sigma$ confidence level (2 degrees of freedom) for 3 calendar years at the BR2 reactor for the baseline proposal (black line) which includes 2 tons of SoLid, and 1 ton of the CHANDLER-enhanced SoLid* (1 ton SoLid + 1 ton SoLid* in blue line). The black dashed line shows the SoLid sensitivity without SoLid*. The blue region is the 95% confidence level region for the reactor antineutrino anomaly, whereas the red region is the corresponding one for the gallium anomaly, both according to Ref. [66]. The black dots are the respective best-fit points.
The Earth shines as a faint antineutrino star radiating into space more than $10^{25}$ antineutrinos every second and superimposed on this is a 1% glow from the patchwork of man-made nuclear reactors. Geoneutrino studies can provide transformative insights into the source of power driving plate tectonics, mantle convection, and the geodynamo. Data from these studies also provides critical insights into what were the building blocks involved in making the Earth from the debris in the accretion disk of the solar nebular. Moreover, the Earth’s geoneutrino signal is the background on the signal used for remote monitoring of nuclear reactors. Therefore, far from the Earth the global signal is bright, whereas close to a reactor (10 to 100s km) its reactor signal overwhelms the total signal. In 2015 our multi-disciplinary research team of particle physicists and geoscientists created an Antineutrino Global Map (AGM 2015, see Fig. 11) based on a quantitative model of the distribution and abundance of potassium, thorium, and uranium inside the Earth. In addition, overlain onto the Earth’s signal AGM 2015 records the distribution and power flux of the global nuclear reactor signal. Considerable discussion remains regarding the amount of radiogenic power available to drive the Earth’s engine. Ongoing geological studies are providing critical insights into spatial variations of the Earth’s signal. We are now capable of conducting geo-neutrinoimaging of the Earth’s interior, which allows us to test models on the nature of seismically imaged structures in the deep mantle [13].

FIG. 11. AGM2015 maps, high resolution version can be found here: https://www.nga.mil/MediaRoom/PressReleases/Pages/Antineutrino.aspx
COSMIC BACKGROUNDS IN SURFACE MEASUREMENTS

MICHAEL P. MENDEHALL (NIST), for the PROSPECT collaboration

Past neutrino experiments typically operated with a few kilometers of overburden shielding from the surface radiation environment. For measuring close to reactor neutrino sources — such as in proposed few-meter-baseline oscillation searches, or safeguards monitoring — operating near the surface is necessary, with an associated need for understanding and mitigating near-surface background mechanisms.

Most $\nu_e$ detectors use inverse beta decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$, with a distinctive correlated signal between positron interactions in the first few nanoseconds, and a neutron capture many microseconds later. This correlation timescale permits excellent rejection of background processes lacking neutrons. Deep underground, neutrons come from fissioning radioactive nuclei; closer to the surface, muon spallation generates neutron showers. Within a few meters of the surface, these processes are overwhelmed by the far higher neutron flux from cosmic ray showers originating in the upper atmosphere. Neutrons below $\sim 20\text{ MeV}$ kinetic energy, the energy scale of fissioning spallation fragments, are easily blocked by a few tens of centimeters of hydrogenous shielding. Higher-energy neutrons, produced at cosmic ray shower energy scales, may penetrate through meters of material before producing secondary showers containing several fission-energy-scale neutrons. Monte Carlo simulations of detector response to cosmic backgrounds (see Fig. 12) indicate that these extra-fast $E \gtrsim 20\text{ MeV}$ neutrons are the primary culprit for “IBD-like” backgrounds mimicking $\nu_e$ signals, often via spallation showers near the detector active volume. Such simulations are in good agreement with observed neutron-correlated “IBD-like” distributions in the Prospect Collaboration’s small prototype detectors, and are used to extrapolate to larger designs.

Backgrounds are mitigated by shielding against the cosmic neutron flux and vetoing non-IBD coincidences in the active volume. Simulations help to optimize weight-, size-, and cost-effective shielding against the downward-directed high-energy cosmic neutron flux. Most particles emerging from the shielding into active detector volume will interact within $\sim 10\text{ cm}$ of the surface, allowing background events outside an interior fiducial volume to be vetoed. Extra-fast $\gtrsim 20\text{ MeV}$ neutrons can penetrate deeper before elastic and inelastic scattering, producing gammas, recoil protons, and secondary neutrons — which can subsequently thermalize and capture in an “IBD-like” coincidence. Detector segmentation and gamma/proton pulse-shape discrimination (PSD) work together to isolate and identify “un-positronlike” characteristics of fast neutron interactions.

![FIG. 12. Cosmic neutron background at surface and under 1-MWE shield.](image-url)
The miniTimeCube (mTC) is a compact antineutrino detector designed to explore the benefits of using fast timing to reconstruct inverse beta decay event topology (see Fig. 13) [67]. The detection volume is a $(13\times13\times13)$ cm$^3$ cube of plastic scintillator doped with $^{10}$B and surrounded by 24 microchannel plate photomultiplier tubes with $8\times8$ segmented anode arrays. Anode signals are recorded by custom electronics utilizing multi-gigasample per second waveform digitizing integrated circuits developed at the University of Hawaii. Initial reconstruction algorithms studied in simulation indicate that the mTC will achieve antineutrino energy resolution of 10-20% over most of the reactor antineutrino energy spectrum, and will be capable of measuring incident antineutrino directionality more precisely than any other operating antineutrino detector. The mTC is currently deployed about 5 m from the core of the National Institute of Standards and Technology Center for Neutron Research reactor in Gaithersburg, Maryland, with the detector residing inside a special shielding cave to reduce neutron and gamma ray backgrounds. Simulations of signal and uncorrelated background events suggest an expected signal-to-noise ratio of 1:1, with 1 antineutrino event per day that passes all selection criteria. Initial data collection is beginning in early 2016, and will be used to assess the full background conditions and perform initial physics studies.

**FIG. 13.** (Left) Screenshot of a GEANT and MATLAB simulation of an antineutrino interaction in the mTC. (Right) Simulated directional reconstruction of the mTC, as constructed (“MTC Boron”), compared with Double CHOOZ and two hypothetical detectors, a 138 kT detector (“TREND”), and an MTC constructed from a lithium doped scintillator (“MTC Li”).
NEUTRINO EXPERIMENT FOR OSCILLATION AT SHORT BASELINE (NEOS)
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NEOS aims at verification of short baseline neutrino oscillation by existence of a sterile neutrino. The experiment takes place in the tendon gallery of a 3 GWth commercial reactor, located in Yeonggwang, South Korea. The baseline is about 25 m and the overburden provided by the reactor building is higher than 30 m.w.e in all directions. The inverse beta decay of the anti electron neutrino is detected by a 1000 L of homogeneous liquid scintillator target. 10% of UG-F (DIN based LS) has been mixed to the LAB based LS to enhance the pulse shape discrimination power. Loading 0.5% of Gd has made the neutron capture time 7 µs. The experiment has started to take data from August 2015. About 45 days of reactor off data have been acquired during the reactor overhaul maintenance period, and the data with the reactor on have been being accumulated since 20th of October 2015. As a preliminary result, we report about 2,000 inverse beta decay events are detected per day, with signal to background ratio about 20.

FIG. 14. Candidates of inverse beta decay events (green), with the reported electric power of the reactor (purple).
PROGRESS ON DEVELOPING A SEGMENTED DETECTOR USING ZNS:Ag/6LiF

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Under previous work supported by DOE NA-22, we have developed a promising segmented detector technology based on the combination of standard organic plastic scintillator and ZnS:Ag/6LiF. The integrated readout of these inhomogeneous segments allows relatively unambiguous particle identification—the key to background rejection enabling above ground operation through both pulse-shape discrimination and event topology. A small 4-segment prototype system \[68\] was tested at the Sano Onofre Nuclear Generating Station (SONGS) in 2011 and demonstrated a \(10^5\) rejection of backgrounds in an aboveground deployment without any passive shielding. More recent work, supported by the DOS-Vfund, has greatly improved the efficiency and uniformity of individual segments \[69\].

The current work is focused on understanding the response of the system as its size and number of segments are scaled up. Our current understanding suggests that the primary source of un-rejected backgrounds arise from cosmogenic fast neutrons mimicking the topology of an antineutrino event. We have performed simulations of the expected detector response to fast neutrons using incident cosmogenic neutron spectra. These simulations slightly overestimate, but are roughly consistent with, the measured background rate from the previous aboveground deployment. The simulated response of the detector system to increasing detector size and number of segments is shown in the figure below for a potential aboveground deployment 25m from SONGS. As expected, we see a rapid improvement in the efficiency of the detector for antineutrino selection due to the reduction in the fractional surface leakage effects followed by a simple scaling with detector mass. The overall detector efficiency for antineutrino events appears to be roughly 10% for detectors of at least 25 segments. What is most encouraging is the significant improvement in the background rejection as the detector scales up in size. In fact, as the detector increases from 49 to 121 segments (a factor of 2.5 in mass), the overall background rate only increases by about 20%. In the end, we feel that a 20’ shipping container filled with 520 segments would provide a detector that could successfully operate above ground for many potential safeguards applications. If placed 20 m from a reactor, it would be expected to record \(\sim 5\) events/day/MWth and would have an expected background rate of only \(\sim 400\) events/day from cosmogenic neutrons.

FIG. 15. The simulated response of the segmented scintillator detector system to antineutrino events (antineu) and cosmogenic fast neutron background events (cosmic) as a function of detector size. The signal events scale the mass of the detector while the background events do not, indicating the improvement in background rejection as the detector is scaled up in size.
**NULAT: A NOVEL DESIGN FOR A REACTOR ANTI-NEUTRINO DETECTOR**

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The NuLat detector \[70\] is a brand-new approach to achieve near-ideal detector segmentation, resulting in the most direct rejection of backgrounds using spatial, temporal and topological cuts. NuLat uses a Raghavan Optical Lattice (ROL) to transport light from energy deposits in individual detector voxels onto six pixilated detector faces providing for complete 3-D topological studies with position resolution equal to or better than an individual voxel (2.5 in)\(^3\). NuLat will demonstrate reactor monitoring capabilities of a small solid surface detector; show directional sensitivity for fast neutrons; and probe anomalies in the reactor-antineutrino spectrum by employing a ROL detector made from \(^6\)Li−loaded (0.5% by wt) plastic polyvinyl toluene scintillator cubes, NuLat provides:

1. exceptional energy resolution for prompt betas from IBD events,
2. a very unique start signal of a largely single-voxel (PSD identified) positron in coincidence with signs of its annihilation gammas,
3. a mono-energetic and PSD distinguished stop signal due to neutron capture on \(^6\)Li,
4. digital fine segmentation into \(N \times N \times N\) 250 mL detectors,
5. complete event topology, \(E(x,y,z,t)\),
6. no energy loss to internal walls,
7. a unique topological ensemble for true IBD events that enables statistical rejection of backgrounds not oriented with the reactor direction,
8. fast timing to distinguish the positron energy loss and decay of ortho-positronium,
9. an extremely minimal corner fiducial-cut requirement,
10. a small footprint allowing for deployment very close to a research reactor and just outside containment of a commercial power plant,
11. true portability,
12. minimal R&D required for deployment, and
13. uniquely able to uniformly deploy radon-222 gas as an ideal calibration.

The ROL concept uses a high index of refraction material divided into voxels by a lower index of refraction material (Fig. 16). The NuLat collaboration is currently building a five cubed \(^6\)Li detector (the ROL 53 detector) for deployment at a commercial reactor (\(\sim 50 \nu/d\) with \(S/B\) 10), in the mTC cave at NIST (15 \(\nu/d\)), and underground at KURF to systematically study time-correlated \(\mu\)-induced backgrounds as a function of muon rate.

**FIG. 16.** mTC shielding cave at NIST. The CAD rendering shows the entire NuLat layout: reactor core + cave + rails that will allow 2 m flexibility to move the cave and change detector baseline. The top left inset shows light transport down all three orthogonal channels in an acrylic mock-up.
If the energy of a neutrino is below roughly 50 MeV, then it can coherently scatter off the constituents of a germanium nucleus, resulting in the respective cross section being enhanced by roughly the square of the number of neutrons in the nucleus. The maximal expected signal of this interaction with typical reactor antineutrinos ($E_{\nu} < 8$ MeV) is roughly 450 eV, thus, a low energy threshold is required to detect coherent neutrino-nucleus scattering (CNNS).

During the last decade various groups tried to measure CNNS near nuclear reactors with point contact germanium (PCGe) detectors \cite{71-73}. Unfortunately, these projects failed, mostly due to high electronic noise and high background levels. PCGe detectors are cylindrical semiconductor diodes. On one base of the cylinder they have a circular electrode embedded, while most of the remaining surface is covered by a different electrode. This arrangement allows it to reach relatively low capacitances of a few pF and thus to keep the electronic noise small. The electronic noise directly limits the obtainable energy threshold \cite{74}. In order to observe the CNNS signal next to accidentally triggered events an electronic noise of less than 100 eV FWHM is required for a $\sim 1$ kg detector. It has only been in the last few years that detectors with this capability have actually become available.

Although higher numbers of antineutrinos (order of $10^{13}$) are expected to be present near reactor cores ($\sim 15$ m distance), the actual signal induced by coherently scattered neutrinos is weak and background levels of below 1 count/keV/kg/day are required to measure the signal. It was not until recently that these levels were reached at a shallow depth with modern shielding and neutron moderation techniques \cite{75}.

As discussed, the requirements for such an experiment (sufficiently low electronic noise and low backgrounds) are accessible (a typical situation is represented in Fig. 17). Thus, it is a good time to reconsider this technology’s potential for a CNNS measurement.
We have updated the ENDF/B decay data sub-library to include beta intensities from TAGS measurements and used it with the JEFF yields to calculate antineutrino spectra. This allowed us to identify the nuclides that contribute the most at different energy regions in order to assess the quality and reliability of the decay and fission data. Additionally, we derived a systematic of the cross-section integrated antineutrino spectra as a function of the Z and A of the target, analogous to the one for beta-delayed neutrons. It has been known for a while that there are a few issues with the thermal $^{235}$U thermal ENDF/B yields; additionally, since these yields were last updated in 1993, they are no longer fully compatible with recent decay data. We critically reviewed these yields and corrections were applied to account for a) erroneous yields, b) newly measured and better estimates of isomeric ratios, and c) consistency with decay data. The thermal $^{235}$U antineutrino spectrum calculated with the corrected yields is in much better agreement with the spectrum calculated with the JEFF yields. Moreover, an excess of electrons observed at around 5 MeV using the original yields disappears once the corrected yields are used, see Fig. 18. In order to continue improving the data used in summation calculations, we have identified the $^{96}$Y isomeric ratio as an important quantity that would merit a measurement. Currently only estimates are available, which don’t agree, leading to an uncertainty of about 5 % in the antineutrino spectrum at around 5 MeV.

**FIG. 18.** Calculated electron spectrum divided by the ILL measurement for three different choices of fission yield data: a) corrected ENDF/B yields, b) original ENDF/B yields and c) JEFF yields.
The physics goal of the SoLid experiment is to make a measurement of antineutrinos at close distance from the SCKCEN BR2 reactor using a new detector technology to deliver unprecedented sensitivity in the search for new oscillations. It will test the reactor anomaly by measuring the antineutrino spectrum as a function of distance and energy to confirm or reject the hypothesis of a new neutral state called a sterile neutrino. At the same time, it will provide one of the most precise measurements of a pure $^{235}\text{U}$ anti-neutrino spectrum, an essential ingredient for the improvement of the reactor flux calculation. The use of a different technology combined with a High Enriched Uranium core also enables a very specific measurement complementary to the recent power reactor data. The environment of a research reactor is a challenging one: the reactor is close to the surface, and the core produces a significant amount of background radiation that correlates in time with the measurement. The space available is tight, security and safety is high and access limited. The detector technology proposed by SoLid \[76\] is a change of approach: it utilizes small size EJ-

![FIG. 19. SoLid detector element (voxel) with fibre read out (top left). Scintillation signal from PVT in red and ZnS in blue (bottom left). 288 kg SoLid sub-module made of 2403 voxels, 288 channels and 288 read out channels (right).](image)

200 Polyvinyl Toluene (PVT) cubes (called voxel) covered with a $^{6}\text{LiF:ZnS(Ag)}$ ND sheets from scintacor \[77\] to construct the target volume of the detector (see Fig. 19). The Inverse Beta Decay (IBD) products close to the interaction points enabling accurate position resolution, which reduces the impact of external backgrounds. The PVT is used to detect the positron with good energy resolution ($\delta E/E \sim 14% / \sqrt{E}$ at 1 MeV has been demonstrated). The $^{6}\text{LiF:ZnS(Ag)}$ layer provide a neutron signal insensitive to gamma-rays and providing localization of the neutron capture. The result is the possibility to use most of the active volume as the fiducial target with high detection efficiency and containment of energy. The compactness of the design means it can fit easily in tight space around reactors reducing the need for fiducialization with large energy catcher and buffer volume around the target. The detector only requires a limited external shielding to reduce background and use the new imaging capability provided by 3D segmentation to reject all type of background in ways not achievable with previous detectors. The scintillation signal is collected by orthogonal wavelength shifting fibers and read out by multi pixels photon counter from Hamamatsu. The calibration of the detector is also facilitated by the segmentation: the detector is an excellent cosmic muons tracking device. Muons can be used for calibration and monitoring of the energy scale. Using this methods, we demonstrated sub-percent level equalization of the voxel energy response with the first detector sub-module built and deployed at BR2 in winter 2014. Phase I of the experiment is expected to start in the second half of 2016 with 2 tonnes of fiducial volume. A phase II with the addition of a CHANDLER module is planned to reach higher sensitivity: more details on the sensitivity of SoLid can be found in the CHANDLER section.
Looking toward the future of massive water Cherenkov detectors in general and Super-Kamiokande in specific, work has been ongoing toward realizing the ideas first laid out in Antineutrino Spectroscopy with Large Water Cherenkov Detectors, a top-cited paper published in Physical Review Letters [78]. In a nutshell, the idea is to enrich Super-K’s water with dissolved gadolinium [Gd], in the form of a gadolinium compound such as gadolinium chloride or gadolinium sulfate. With just 0.2% by mass of gadolinium sulfate, $\text{Gd}_2(\text{SO}_4)_3$, dissolved in the water, more than 90% of free neutrons will be captured on gadolinium, emitting an easily visible 8.0 MeV gamma cascade in the process. This will uniquely tag inverse beta reactions: $\nu_e + \text{proton} \rightarrow e^+ + \text{neutron}$. Indeed, gadolinium’s ability to identify if a free neutron is present in the final state will provide a wide variety of physics benefits to Super-Kamiokande and other planned water Cherenkov detectors. Some of these include:

1. Enhanced differentiation between neutrinos and antineutrinos for long-baseline and atmospheric neutrino studies, aiding oscillation and CP measurements, and CPT tests.

2. Extended proton decay limits, and greater proton decay discovery potential. Backgrounds can be reduced by 83% by requiring no neutron in the final state.

3. Vastly improved supernova neutrino response to both the diffuse supernova neutrino background as well as to bursts emitted by core collapse supernovas in our own galaxy.

4. The ability to detect the presence of hidden nuclear reactors via their antineutrino emissions at far-field monitoring distances, i.e. from across national boundaries.

An experimental chamber was excavated in the Kamioka mine very close to the Super-K site. There, a dedicated large-scale gadolinium test facility including a 200-ton scale model of Super-K - has been assembled. Known as EGADS (Evaluating Gadolinium’s Action on Detector Systems), the 200-ton detector has been fully loaded with a 0.2% solution of $\text{Gd}_2(\text{SO}_4)_3$ since April 2015. The transparency of the water in this Gd-loaded detector is now comparable to that of Super-K’s ultrapure water, a remarkable technical achievement.

Based primarily on EGADS’s results, a formal decision to move forward with Gd-loading has recently been made by the Super-Kamiokande Collaboration. The official statement issued by the Collaboration reads as follows:

On June 27, 2015, the Super-Kamiokande Collaboration approved the Super-K-Gd project, which will enhance antineutrino detectability by dissolving gadolinium into the water of Super-K. The actual schedule of the project, including refurbishment of the tank and Gd-loading time, will be determined soon, taking into account the T2K schedule.

In addition to Super-Kamiokande, other planned projects looking at (or based on) this new technology include WATCHMAN, ANNIE, $\nu$PRISM, TITUS, and Hyper-Kamiokande.
PRIOR AAP WORKSHOPS

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2. AAP 2014, December 15–16, 2014, http://aap2014.in2p3.fr
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