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Neutrinos, Dark Matter and Nuclear Detection

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ABSTRACT

Solutions to problems in nuclear non-proliferation and counter-terrorism may be found at the forefront of modern physics. Neutrino oscillation experiments, dark matter searches, and high energy astrophysics, are based on technology advances that have may also have application to nuclear detection. The detection problems share many characteristics, including energy scales, time structures, particle-type, and, of course, the combination of high backgrounds and low signal levels. This convergence of basic and applied physics is realized in non-proliferation and homeland security projects at Lawrence Livermore National Laboratory. Examples described here include reactor anti-neutrino monitoring, dual-phase noble liquid TPC development, gamma-ray telescopes, and nuclear resonance fluorescence.

1.0 INTRODUCTION

Last year, Lawrence Livermore National Laboratory hosted the third in a series of Applied Antineutrino Workshops, with the goal of bringing together the neutrino physics and non-proliferation communities. The meeting was a remarkable and resonant example of the potential for frontier basic physics to impact nuclear detection capabilities for counter-proliferation and counter-terrorism.

The goals of the workshop were to

- Provide the nonproliferation community with a definitive resource about antineutrino detection technologies;
- Help the physics community understand the scope of the nonproliferation problem as it relates to nuclear explosions and nuclear materials, and explain what methods are used now;
- Highlight the scientific and technological overlap between antineutrino research and nonproliferation and nuclear materials/arms control research.

In sessions with titles like “Introduction to Safeguards and Cooperative Monitoring,” “Antineutrino Spectral Modeling and Experiments,” and “Integration of Antineutrino Detectors into Nonproliferation Regimes,” participants reached the conclusions that antineutrino detectors can clearly be used to monitor nuclear reactors at 10-100 m , and that there is strong overlap between reactor monitoring and detector development for next generation physics experiments.

The application of antineutrino research to safeguards, documented by the Livermore workshop, is one example of the potential impact that forefront basic physics can have on problems in nuclear non-proliferation and counter-terrorism. At Livermore, scientists are involved in dark matter searches and high-energy

astrophysics, as well as neutrino oscillation experiments, in order to take advantage of overlaps with nuclear detection. These detection problems share many characteristics, including energy scales, time structures, particle-type, and, of course, the combination of high backgrounds and low signal levels.

1.1 Reactor Antineutrino Monitoring

The last decade has seen a stream of discoveries about neutrinos, using a range of detection technologies. The neutrino sector of particle physics is rich with unknown and newly discovered physics, and increasingly provides a direct challenge to the so-called "Standard Model" of the strong, weak and electromagnetic interactions. It represents an extremely active field of research, and a high priority for US and national science funding agencies. A rough recent chronology would include the 1998 discovery by Super-Kamiodande of atmospheric neutrino oscillations using a 50 Kiloton water Cerenkov detector [1], the observation by the Sudbury Neutrino Obseratory (SNO) of both disappearance and appearance phenomena in a 1 Kiloton heavy water Cerenkov vessel [2], and the observation by KamLAND in 2003 of oscillation of reactor electron antineutrinos in a 1 Kiloton liquid scintillator detector. [3] Taken together, these experiments have established the neutrino mass differences, and 2 of 3 neutrino mixing angles.

There have also been a series of experiments designed to use the neutrinos (actually antineutrinos, produced in the β-decay of neutron-rich fission products) produced in nuclear reactors to study the neutrino sector. Some of the results of these experiments are summarized in Figure 1. [3] These experiments were important for detector development, particularly liquid scintillator technology, and culminated in the KamLAND's first-ever observation of electron antineutrino oscillations, using remote (200 km standoff) Japanese reactors.

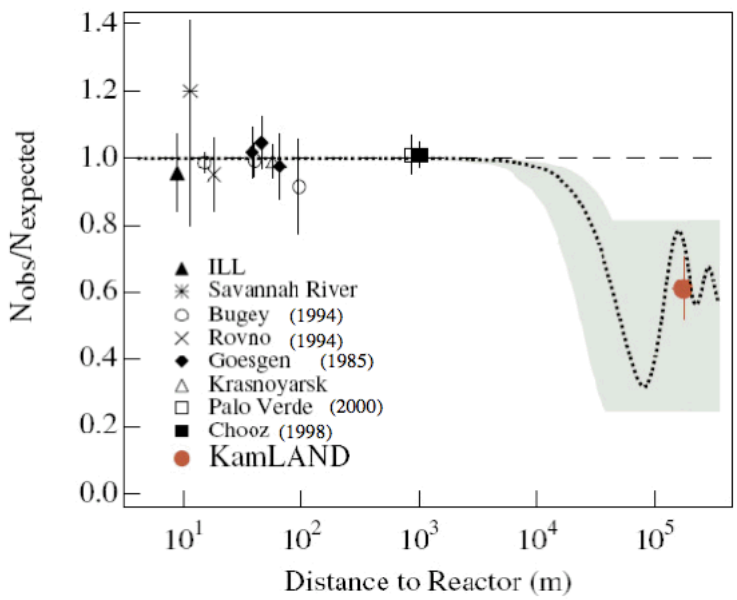

Figure 1: Summary of reactor antineutrino experiments. $N_{expected}$ is the electron number of antineutrinos that would be counted in the absence of oscillations. Prior to KamLAND, detetors were not far enough from the reactor to be able to resolve the disappearance of electron antineutrinos.

But the reactor experiments generally suffer from systematic uncertainties from the changes in antineutrino flux caused by the burn-up of fuel in the reactor. Burn-up gradually replaces the uranium fuel with plutonium, which has different antineutrino emission characteristics. In 1994, a group from the Kurchatov Institute,

working at Rovno, first noted that these systematics could be turned around and used to monitor burn-up in the reactor core. [4]

Practical use required the greater understanding of the oscillation mechanism of neutrinos built up since then, as well as simplifications in the detection technology following a decade of detector development. In 2002, Bernstein et al. were able to propose a realistic detector for monitoring reactor power and plutonium content in real time. [5] The .6 ton, ~1 m^3 liquid scintillator detector, SONGS1, was designed for ease of deployment, simplicity of operation, and low cost. It was operated remotely for 18 months in 2005 and 2006 at a 25 m standoff from the 3.5 GWth core of the San Onofre Nuclear Generating Station in California. The results produced by the SONGS1 detector clearly demonstrated the efficacy of "near-field" monitoring of a nuclear reactor using antineutrinos. At 10% efficiency, SONGS1 recorded 400 antineutrino counts per day, sufficient to determine reactor on/off status in 4 hours; make a 3% relative power measurement in 7 days, and observe 75 kg in-growth of plutonium with 3 months of data. The results are displayed graphically in Figure 2.

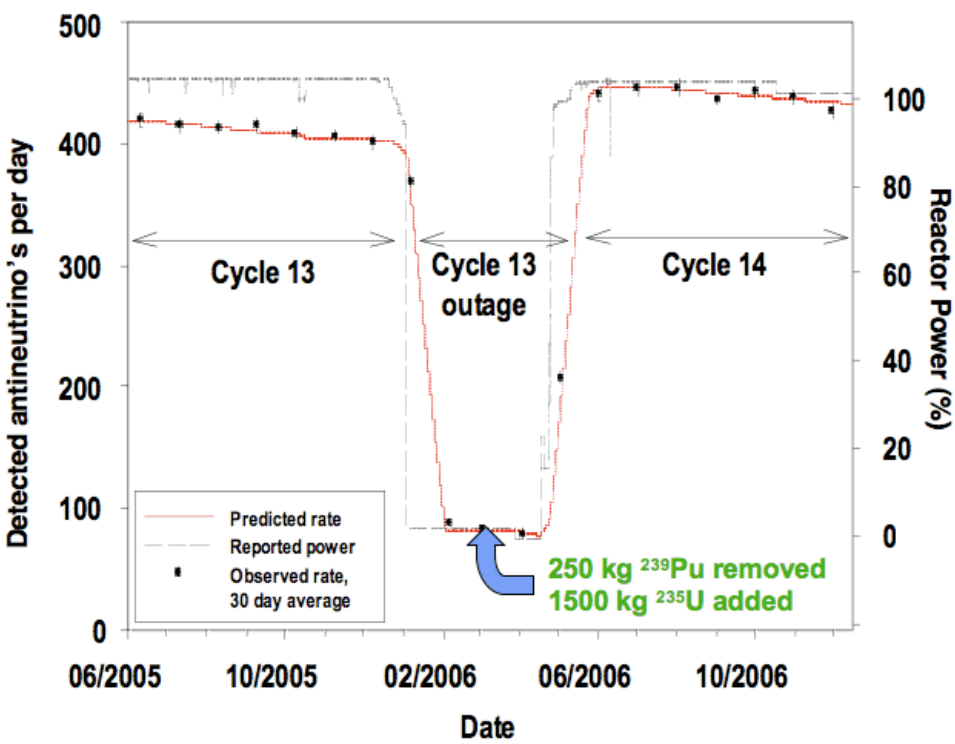

Figure 2: Results from SONGS1, clearly showing the correlation between antineutrino count rate and reactor power, as well as the effects of burn-up.

The next steps in developing this technique for reactor monitoring will probably take place as part of the Double Chooz experiment, which is designed to measure the remaining unknown neutrino mass matrix mixing angle, θ_{13}. [6] Double Chooz will obtain exceptionally high statistics as well as energy spectra of reactor antineutrinos under controlled conditions, thus providing essential and extensive benchmarking for future nonproliferation efforts.

Another line of inquiry for reactor antineutrino research is suggested by the KamLAND result highlighted in Figure 1. KamLAND demonstrated that reactor antineutrinos could be clearly identified and measured up to

100 km from the core, with excellent signal to background. This result suggests that antineutrino monitoring could be used to exclude of confirm the existence of undeclared nuclear reactors over large geographical areas. At this point, though, such "standoff" detection would require very large detectors. For example, based the San Onofre results, it can be estimated that SONGS1 – at a cost of $250K, would detect 16 antineutrinos in a year at a distance of 250 m from a 10 MWth reactor, with no background. KamLAND, which is also a liquid scintillator detector, only 6000 times bigger, would yield the same sensitivity at 6 km standoff. The cost, though, is estimated at $20M. A 45 m pure water detector, like Super-Kamiodande, might be capable of detection at 30 km, for an estimated cost of $100M.

Another approach, being pursued at Lawrence Livermore, is to develop dual phase noble liquid detectors for the detection of coherent antineutrino scattering, an as-yet unobserved process that is, nonetheless, firmly grounded in the theory of neutrino interactions. Coherent scattering is predicted to have a cross section in, for example, argon which is two orders-of-magnitude greater than proton inverse β decay, the method common to many current detectors. A dual phase argon coherent scatter detector with sensitivity equivalent to SONGS1 is estimated to be 10-100 times smaller, depending on achievable detection efficiency. Currently, the dual-phase technology is also being developed for dark matter WIMP searches. Recently, the XENON-10 collaboration, in which Lawrence Livermore participates, proved the utility of the dual-phase approach in reporting the world's best limits on WIMP dark matter using a dual-phase Xenon detector at the Gran Sasso Underground Laboratory. [7]

1.2 Gamma-ray Astrophysics and Hand-held Detectors

While advances in neutrino physics and dark matter detection technology hold promise for enhancing reactor safeguards and nuclear material accountancy, developments spurred by high-energy astrophysics are enabling new architectures for the detection, identification and interdiction of radioactive sources. A collaboration including Lawrence Livermore, Caltech, Columbia University, and the Dutch Space Research Institute, recently flew the HEFT (High Energy Focusing Telescope) gamma-ray telescope featuring arc minute angular resolution and 1% energy resolution at 60 keV on a high-altitude balloon. The detector consisted of pixelated CdZnTe semiconductor crystals bonded to a custom analog signal integrated circuit (ASIC) that achieved extremely low noise, low power, robust performance, while delivering world-record energy resolution.

In parallel, the same detector package was adapted for a prototype hand-held radiation detection device. The high energy resolution of CdZnTe is effective at reducing false alarms caused by, for example, non-fissile sources, while its room temperature, low-power operation allows extended use in portable devices. By mounting the detector in a functioning cell-phone, it is possible to produce a network of radiation sensors, capable of autonomous reporting on radiation sources.

Currently, Lawrence Livermore is developing a prototype of this system called Ultra PeRL, an intelligent personal radiation locator. Ultra PeRL is designed to detect gamma rays and neutrons, characterize the source spectroscopically, locate the target using the inherent directionality of the pixelated detector, and location/orientation sensors included in the package, and communicate the findings to a coordinating location using wireless technology. Like the cell phone, the system is small, low-power, autonomous, and, potentially, ubiquitous.

Meanwhile, HEFT achieved a flawless 30-hour flight in May 2005, during which 18 individual science observations were recorded, including active galactic nuclei in outburst, supernova remnants, and assorted compact objects. Data analysis is underway, and it is already clear that the technology advance represented by

HEFT has enabled new discoveries.

1.3 Nuclear Resonance Fluorescence for Cargo Container Inspection

One of the most daunting challenges in protecting borders is to inspect the huge volume of cargo container shipping that pours through ports for fissile material. A new approach suggested by Pruett et al. exploits nuclear fluorescence (NRF) to detect specific isotopes in the presence of shielding with quantifiably low false -positive and false-negative alarm rates. [8] The technique relies on a bright, narrow bandwidth, tunable gamma-ray source to resonantly excite nuclear transitions. Such sources have been demonstrated based on Thompson up-scattering of laser light by low-emittance electron beams. [9]

In order for NRF to be feasible as an interrogation technique, it is necessary to identify useful resonances in fissionable material that, while theoretically present, have not yet been observed. This was the subject of a recent experiment performed by Lawrence Livermore and collaborators from PNNL and Passport Systems, Inc. The experiment uses a 3 MeV Van de Graf at the MIT High Voltage Research Laboratory to search for resonances in ^{239}Pu and ^{235}U. The measurements have thus far revealed 13 new transitions from NRF excitations in ^{239}Pu and 10 transitions in ^{235}U between 2 and 2.5 MeV. [10]

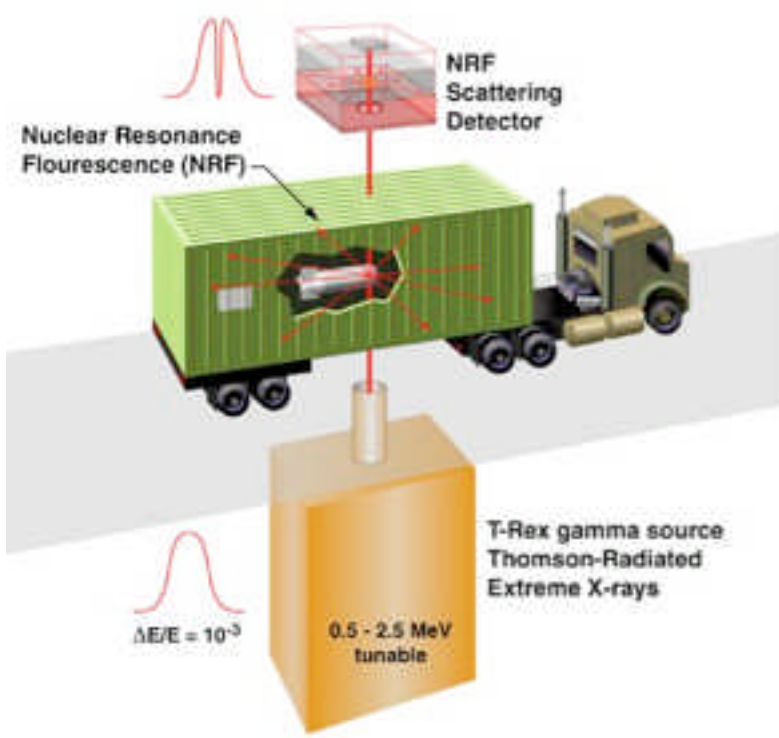

Figure 3: Cargo Container Interrogation concept based on T-REX sources and Nuclear Resonance Fluorescence signatures. Resonant photons scatter from materials of interest either in the container, or from a witness foil in the NFR scattering detector.

At Livermore, the mono-energetic Thompson x-ray source PLEIADES [10] is being upgraded from ~60 to ~700 keV. The new gamma-ray source, dubbed T-REX (Thompson-Radiated Extreme X-rays), will be used to test the NRF interrogation concept using depleted uranium as a target. At the same time, T-REX will represent

a forefront light source capability with a peak brilliance at 1 MeV exceeding any synchrotron source by 15 orders of magnitude. The demonstration of such a source may enable photo-nuclear research as rich as is currently commonplace using x-ray light sources as a probe of atomic systems.

1.4 Conclusion

Four areas at the forefront of physics have been discussed as examples of the synergy between basic research and applications to nuclear detection: neutrino oscillation experiments, dark matter searches, high-energy astrophysics, and photo-nuclear physics. This convergence of basic and applied physics is realized in non-proliferation and homeland security projects at Lawrence Livermore National Laboratory, including reactor anti-neutrino monitoring, dual-phase noble liquid TPC development, gamma-ray telescopes, and nuclear resonance fluorescence experiments.

REFERENCES

[1] Fukuda et al., Phys. Rev. Lett. 81, 1562 (1998)

[2] Ahmad et al., Phys. Rev. Lett. 89, 011301 (2002).

[3] Eguchi et al., Phys. Rev. Lett. 90, 021802 (2003).

[4] Klimov et al., Atomic Energy 76, 123 (1994).

[5] Bernstein et al., J. Appl. Phys. 91, 4672 (2002).

[6] Ardellier et al., *Double Chooz: A Search for the Neutrino Mixing Angle* θ_{13}, arcXiv:HEP-ex/0606025v4, (2006).

[7] Aprile, *First Results from the XENON10 Dark Matter Experiment at the Gran Sasso Underground Laboratory*, 2007 APS April Meeting, Jacksonville, FL, April 14-17, 2007.

[8] Pruet et al., J. Appl. Phys. 99, 123102 (2006).

[9] Hartemann et al., Phys. Rev. E64, 016501 (2001).

[10] Johnson et al., *Strong Dipole Excitations Around 2 MeV in* ^{235}U *and* ^{239}Pu, in preparation.

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