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Reactor Monitoring with Antineutrino Detectors

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Nuclear reactors have served as the antineutrino source for many fundamental physics experiments. The techniques developed by these experiments make it possible to use these weakly interacting particles for a practical purpose. The large flux of antineutrinos that leaves a reactor carries information about two quantities of interest for safeguards: the reactor power and fissile inventory. Measurements made with antineutrino detectors could therefore offer an alternative means for verifying the power history and fissile inventory of a reactor as part of International Atomic Energy Agency (IAEA) and/or other reactor safeguards regimes. Several efforts to develop this monitoring technique are underway worldwide.

1. Introduction

In the five decades since antineutrinos were first detected using a nuclear reactor as the source [1], these facilities have played host to a large number of neutrino physics experiments. During this time our understanding of neutrino physics and the technology used to detect antineutrinos have matured to the extent that it seems feasible to use these particles for nuclear reactor safeguards, as first proposed three decades ago [2].

Safeguards agencies, such as the IAEA, use an ensemble of procedures and technologies to detect diversion of fissile materials from civil nuclear fuel cycle facilities into weapons programs. Nuclear reactors are the step in the fuel cycle at which plutonium is produced, so effective reactor safeguards are especially important. Current reactor safeguards practice is focused upon tracking fuel assemblies through item accountancy and surveillance, and does not include direct measurements of fissile inventory. While containment and surveillance practices are effective, they are also costly and time consuming for both the agency and the reactor operator. Therefore the prospect of using antineutrino detectors to non-intrusively *measure* the operation of reactors and the evolution of their fuel is especially attractive.

The most likely scenario for antineutrino based cooperative monitoring (e.g. IAEA safeguards) will be the deployment of relatively small (cubic meter scale) detectors within a few tens of meters of a reactor core. Neutrino oscillation searches conducted at these distances at Rovno [3] and Bugey [4] in the 1990's were in many ways prototypes that demonstrated much of the physics required. Once the neutrino oscillation picture became clear at the start of this decade, all the pieces were in place to begin development of detectors specifically tailored to the needs of the safeguards community [5].

2. Antineutrino Production in Reactors and Detection

A more detailed treatment of this topic can be found in a recent review of reactor antineutrino experiments [6]. Antineutrino emission by nuclear reactors arises from the beta decay of neutron-rich fragments produced in heavy element fissions. These reactor antineutrinos are typically detected via the inverse beta decay process on quasi-free protons in a hydrogenous medium (usually scintillator): $\bar{\nu}_e + p \rightarrow e^+ + n$. Time correlated detection of both final state particles provides powerful background rejection.

For the inverse beta process, the measured antineutrino energy spectrum, and thus the average number of detectable antineutrinos produced per fission, differ significantly between the two major fissile elements, ^{235}U and ^{239}Pu (1.92 and 1.45 average detectable antineutrinos per fission, respectively). Hence, as the reactor core evolves and the relative mass fractions and fission rates of ^{235}U and ^{239}Pu change, the number of detected antineutrinos will also change. This relation between the mass fractions of fissile isotopes and the detectable antineutrino flux is known as the burnup effect. Over the course of a typical reactor fuel cycle, this results in a decrease in the detected antineutrino emission rate of about 10%.

3. The SONGS1 detector: a proof of principle demonstration

A collaboration between the Sandia National Laboratories (SNL) and the Lawrence Livermore National Laboratory (LLNL) has been developing antineutrino detectors for reactor safeguards since about 2000. Our particular focus is on demonstrating to both the physics and safeguards communities that antineutrino based monitoring is feasible. This involves developing detectors that are simple to construct, operate, and maintain, and that are sufficiently robust and utilize materials suitable for a commercial reactor environment, all while maintaining a useful sensitivity to reactor operating parameters.

The SONGS1 detector [7] was operated at the San Onofre Nuclear Generating Station (SONGS) between 2003 and 2006. The active volume comprised 0.64 tons of Gd doped liquid scintillator contained in stainless steel cells . This was surrounded by a water/polyethylene neutron-gamma shield and plastic scintillator muon veto.

The detector was located in the tendon gallery of one of the two PWRs at SONGS, about 25 m from the reactor core and under about 30 m.w.e. overburden. Galleries of this type, which are part of a system for post-tensioning the containment concrete, are a feature of many, but not all, reactor designs. It may therefore be important to consider detector designs that can operate with little or no overburden.

The SONGS1 detector was operated in a completely automatic fashion. Automatic calibration and analysis procedures were implemented and antineutrino detection rate data was transmitted to SNL/LLNL in near real time. An example of the ability to track changes in reactor thermal power is given in Fig. 1. A reactor scram (emergency shutdown) could be observed within 5 hours of its occurrence at 99.9% confidence. Integrating the antineutrino detection rate data over a 24 hour period yielded a relative power monitoring precision of about 8%, while increasing the averaging period to 7 days yielded a precision of about 3% [8].

Increasing the averaging time to 30 days allowed observation of the fuel burnup [9] (Fig. 2). The relatively simple calibration procedure was able to maintain constant detector efficiency to better than 1% over the 18 month observation period. The decrease in rate due to fuel evolu-

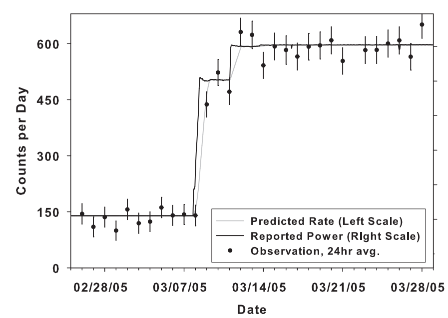

Figure 1. The SONGS Unit 2 Reactor ramping from zero to full power over the course of several days.

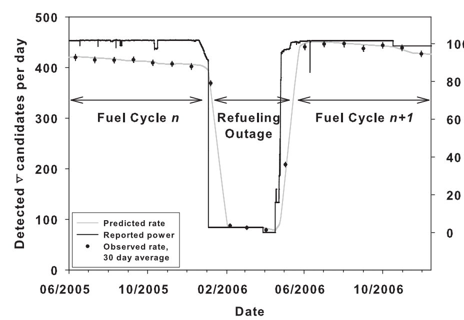

Figure 2. Antineutrino rate measurements before, during, and after a rector refueling outage. The decrease in detection rate as the fuel evolves and the step increase in rate after refueling can be seen.

tion (burnup) and the step increase in rate expected after refueling (exchange of Pu laden fuel for fresh fuel containing only U) were both clearly observed.

4. Global efforts to develop safeguards antineutrino detectors

There are many efforts underway around the world to explore the potential of antineutrino based reactor safegaurds. The evolution of these efforts is summarized in the agenda of the now regular Applied Antineutrino Physics (AAP) Workshops held in 2005, 2006, 2007, 2009 and 2010. The most recent of these meetings [10] provides an excellent summary of the many efforts now underway in the USA, France, Brazil, and Japan. These efforts are investigating several different questions including, but by no means limited to, detector operation with little or no overburden, research reactor monitoring and online refueled reactor monitoring.

5. IAEA Interest

The IAEA is aware of the developments occurring in this field. A representative from the IAEA Novel Technologies group has attended the most recent AAP meetings. An experts meeting of physicists and safeguards practitioners was held at IAEA headquarters in October of 2008 to discuss the capabilities of current and projected antineutrino detection techniques and the needs of the IAEA. Several technology development paths and specific applications for this technique were identified. Most recently, several groups presented recent developments to a broad safeguards audience at the biennial IAEA Safeguards Symposium.

6. Conclusion

Applications of neutrino physics may seem somewhat fanciful, but even with currently available technologies useful reactor monitoring appears feasible. This has been clearly demonstrated by the SONGS1 results. The IAEA has expressed interest in this technique and the Applied Antineutrino Physics community eagerly awaits their guidance as to the steps required to add antineutrino based reactor monitoring to the safeguards toolbox.

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