The Nucifer demonstrator for nuclear reactor monitoring

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Abstract. The Nucifer demonstrator is a prototype device for nuclear reactor monitoring. It pools French and German resources and know-how to meet the International Atomic Energy Agency’s requirements about performing nuclear safeguard measurements in a non-intrusive way. Nucifer detects electron antineutrinos emitted in the decay chains of fission products. Combined with reactor simulations, it provides a promising way to assess both the thermal power and fissile material content of a nuclear core. This article reports on the successful 5 years of operations of Nucifer at the Osiris research reactor, located at the Saclay research center of the French Alternative Energies and Atomic Energy Commission. Nucifer achieved the world’s second-shortest baseline antineutrino detection, 7 m away of a reactor core in severe background conditions, using 145 and 106 days of reactor on and off data, respectively. The future and next steps of the Nucifer project are then briefly discussed.

1. Introduction
In a context of increasing needs for carbon emission-free energy, civilian nuclear energy is likely to play an important role in global energy production, making the list of countries aiming to acquire the technological know-how in this field growing. As a consequence, the International Atomic Energy Agency (IAEA) has been evaluating the potential of new technologies to guarantee that nations use nuclear energy for peaceful purposes only. Neutrino detectors, positioned outside a nuclear facility containment area, may offer the unique ability to non-intrusively monitor any reactor’s operational status, thermal power, and fissile content in real time. As such, the Nucifer detector has been built for long-term and reliable safeguard measurements in the vicinity of operating nuclear reactors. It aims at demonstrating the concept of "neutrinometry" at the pre-industrialized stage. Therefore, well-established detection technologies and commercial components were chosen for the detection system.

2. The Nucifer detector at the Osiris research reactor
Nucifer is installed on the concrete foundation slab of the Osiris reactor building at the French Alternative Energies and Atomic Energy Commission (CEA), in a dedicated room next to the reactor core (see left panel of Fig. 1). The detector is located 7.21 ± 0.11 m away from the core, and is protected by a modest 12 m w.e. overburden, reducing the muon flux by a factor of 2.7 with respect to sea level. In this configuration, radiations from the reactor core are attenuated...
by about 2 m of concrete and 3.5 m of water.

Osiris is a light water experimental reactor of open-core pool type. It operates at a nominal thermal power of 70 MW and typically runs 180 days per year with three-week cycles, the core being refueled by about $1/7$ [1]. The 19.75% enrichment of the nuclear fuel in $^{235}\text{U}$ and the short cycle duration therefore suppress the evolution of the isotopic composition of the nuclear fuel.

The detector in its original design (see right panel of Fig. 1) consists of a 850 L cylindrical liquid scintillator tank, surrounded by an active plastic scintillator veto to tag cosmic ray muons, and two layers of shielding: 14 cm of boron-doped polyethylene to capture neutrons and 10 cm of lead to attenuate external gamma rays [2]. Three additional lead walls have been later erected, to further attenuate the reactor-induced gamma rays [3]. The liquid scintillator is doped with a gadolinium complex to enhance and clearly sign the capture of thermal neutrons [4]. Scintillation light collection is performed by 16 eight-inch Hamamatsu R5912 photomultipliers tubes (PMTs), located on top of the detector vessel. A 25-cm thick acrylic disk separates the PMTs from the target liquid scintillator, and is filled with mineral oil. This so-called buffer volume optically couples the PMTs to the liquid scintillator, enhance the uniformity of the detector energy response, and shields the scintillator from the intrinsic radioactivity of the PMTs.

The analogical output of each of the 16 PMTs is sent to commercial CAEN Charge to Digital Converter (QDC) modules. The acquisition is triggered either by the analogical sum of all PMTs overcoming a hardware threshold equivalent to about 1 MeV or by computer driven LED and random signals. The Data Acquisition system (DAQ) is based on the LabView software, allowing a remote control of the acquisition and a constant monitoring of the safety parameters, such as pressure, liquid level and temperature at various locations in the detector. The Nucifer detector has been operating without any safety failure since its commissioning at Osiris in 2012 [3].

3. Expected antineutrino signal
Reactor antineutrinos are detected through the Inverse Beta Decay (IBD) reaction on free protons in the target volume: $\bar{\nu}_e + p \rightarrow e^+ + n$. The time coincidence between the positron and neutron signals clearly signs an IBD reaction, and efficiently suppresses any backgrounds.

Figure 1. Left: the Nucifer experimental layout at Osiris. East is on the right, and South points to the reader. Right: cut view of the Nucifer detector. The volume is about $3 \times 3 \times 2.4 \text{m}^3$. 

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$^{235}\text{U}$
that could mimic such a signal. The positron signal corresponds to a prompt energy deposition within the liquid scintillator. Measuring the positron energy allows to estimate the incoming $\bar{\nu}_e$ energy: $E_{\text{prompt}} \sim E_{\bar{\nu}_e} - 0.8\, \text{MeV}$. The delayed signal typically occurs $\sim 10 - 100\, \mu\text{s}$ later, and either corresponds to a 2.2 or a 8 MeV gamma ray cascade following the capture of a neutron on a H or a Gd nucleus, respectively. To estimate the expected $\bar{\nu}_e$ interaction rate within Nuifer, detailed core simulations are performed using a follow up of the thermal power as well as the positions of each control rod during the operation of the Osiris reactor [3]. The daily interaction rate depends on the neutrino flux emitted by the reactor, the baseline, the number of target free protons, and the detector efficiency. A total of 913 $\bar{\nu}_e$ per day is expected, with a relative uncertainty of 4.6%, dominated by the knowledge of the reactor-detector baseline (3.1%), the fission cross-sections (2.2%), and the thermal power (2.0%). A tuned Geant 4 Monte Carlo simulation of the detector, including scintillation and PMT light collection, has been used to estimate the global IBD detection efficiency. A 30.3 ± 2.2% efficiency was obtained, leading to an expected detection rate of 277 ± 23 $\bar{\nu}_e$ per day. A detailed discussion about the different sources of detection systematic uncertainties is given in [3].

4. Detector calibration

The Nuifer calibration system is designed to provide an absolute energy scale to the light response of the detector as well as to assess its linearity and stability [2]. A light injection system (LIS), made of Teflon light diffusers connected to Light-Emitting Diodes (LED) by optical fibers, is installed in the target vessel. The LIS is ran and controlled through the acquisition software, and generates Single Photo-Electrons (SPEs) as well as signals with different intensities to test the linearity and stability of the PMTs over their full dynamic range. The LIS allows real time monitoring of both the pedestal and gain of each electronic channel.

Three gamma-emitting sources of few kBq activity ($^{137}\text{Cs}$, $^{60}\text{Co}$ and $^{22}\text{Na}$) were deployed within a vertical tube running along the target central axis to measure the detector energy response. A $^{241}\text{AmBe}$ neutron source of few MBq activity was also used to validate the algorithm searching for correlated pair of events, and to study the neutron capture time and detection efficiency. All these calibration sources were inserted at different elevation levels in the central vertical tube and used to tune the detector’s Geant 4 simulation. A global energy calibration factor of $\sim 340$ p.e./MeV was obtained, corresponding to an intrinsic energy resolution of 10% at 1 MeV at the detector center.

5. Neutrino signal extraction

The neutrino signal is extracted using an optimized algorithm searching for correlated pairs of events. The challenge of such an analysis consists in the statistical separation of IBD events from background events. These events are either caused by random coincidences of single events passing the analysis criteria, or by correlated coincidences, which may originate from cosmic muons and from the reactor core. The data set used in this analysis corresponds to 10 Osiris cycles, accumulated from June 2014 to July 2015, and totals 146 (resp. 106) days of reactor on (resp. off) data [3].

The shape of the reactor antineutrino spectrum and the kinematics of the IBD reaction make the prompt energy deposition ranging from 1.022 MeV to about 8 MeV. The prompt signal energy selection criteria has been optimized to maximize signal over background ratio. Given the steep increase of the background rate in the low energy regime, a 2 MeV lower and 7.1 MeV upper energy cuts are used. The delayed event, associated to the 8 MeV gamma ray cascade following the neutron capture on a Gd nucleus, is selected by applying a lower and upper energy cut of 4.2 MeV and 9.6 MeV, respectively. Such a large delayed energy window accommodates for energy leakages due to the finite size of the target volume. Last but not least, a time coincidence selection criteria is applied: the selected prompt and delayed signals must lie in a $\Delta t_{e^+n} \leq 40\, \mu\text{s}$.
time window, starting right after the selected prompt candidate. This time window corresponds
to twice the expected mean neutron capture time. Because of the severe background conditions,
this time window could not be further extended at the cost of a degraded S/B ratio otherwise.
All events passing those cuts are further required to be more than 100 µs away from a detected
muon. Finally, an isolation selection criteria is applied to all selected prompt-delayed pairs. It
imposes that no energy deposition occurs either 60 µs before the prompt event or 60 µs after the
delayed event. This cut rejects cosmic-ray-induced background with more than two particles in
the same shower.
Even with the additional lead shielding installed after the detector commissioning, the observed
accidental rate of prompt-delayed events was measured to be much higher than the expected
$\bar{\nu}_e$ signal when the reactor was on. However, this high accidental background rate could be
accurately measured and subtracted using the off-time coincidence method. Within the selection
cuts, the accidental rate averaged on the full data set is found to be 69.1 ± 0.1 d$^{-1}$ and
3476.3 ± 0.7 d$^{-1}$ during reactor off and reactor on periods, respectively.
After subtracting the selected IBD candidates from the measured accidental rate, the remaining
sample of correlated pairs is not purely neutrinos. A correlated background component has still
to be measured and subtracted to finally extract a neutrino signal. The most probable correlated
background candidates are fast neutrons created by an inelastic muon interaction (spallation) in
materials above or nearby the detector. A first neutron can scatter off protons in the detector
target, mimicking prompt-like energy deposition. The delayed energy deposition can then either
be mimicked by that same neutron capturing on a Gd nucleus, or another neutron originating
from the same muon-induced shower. The shallow overburden above the Nucifer detector cannot
stop the majority of these atmospheric muons, but is able to significantly attenuate the hadronic
showers produced by cosmic ray interactions in the atmosphere. The remaining correlated back-
ground rate, measured during reactor off periods, is found to be 1145.4 ± 3.4 d$^{-1}$.
The distribution of neutrino events is obtained after subtracting the accidental background and
the correlated background from the raw number of candidate pairs. A statistical sample of
40760 $\bar{\nu}_e$ is obtained, corresponding to an averaged rate of $R_{\text{obs}} = 281 ± 7$ d$^{-1}$ to be compared
to $R_{\text{exp}} = 277 ± 23$ d$^{-1}$ (see section 3). The averaged daily rate as a function of time is shown on
the left panel of figure 2. Each data point (blue diamonds) corresponds to about 5 days of data
taking with its associated statistical uncertainty. The gray shaded area is the rate expectation
above the mean correlated background when the reactor is off, referred as zero level here and
plotted as red dots. The alternations of on and off periods are clearly visible.

6. Sensitivity to the Plutonium content of the core
With the end of the Cold War, hundreds of tons of weapon-grade plutonium were determined to
be surplus to U.S. and Russian defense needs. In April 2010, the US and Russian governments
signed a protocol amending the 2000 Plutonium Management and Disposition Agreement
(PMDA), which commits each country to dispose of no less than 34 metric tons (MT) of excess
weapon-grade plutonium [5]. The current approach is to transform the weapon-grade plutonium
into mixed oxide fuel and irradiate it in reactors.
To estimate Nucifer’s sensitivity to the Plutonium content of the Osiris core, the measured
neutrino rate is used as a reference point. The operation of the Osiris reactor, loaded
with Uranium oxyde-MOX-like fuel elements was simulated with the Monte-Carlo N-Particle
transport Utility for Reactor Evolution (MURE) [6], varying the total amount of $^{239}$Pu in
the core. During standard operations, the Osiris core is loaded with 14.00 ± 0.75 kg of $^{235}$U
and 450 ± 50 g of $^{239}$Pu. Various initial configurations with up to 10 kg of Pu in the initial
composition of the core were then simulated, with a total mass of fissile materials kept to 20
kg. As shown by right panel of figure 2, Nucifer is sensitive to the presence of at least 1.5 kg
Figure 2. Left: Nucifer $\bar{\nu}_e$ rate measurement monitoring the Osirirs nuclear reactor operations. See text for further details. Right: Mean $\bar{\nu}_e$ rate detected by Nucifer (blue diamonds), concatenating Osiris cycles. The gray area shows the interval at 95% C.L. The other horizontal lines illustrate the predicted evolution of the detected flux for an increasing mass of $^{239}\text{Pu}$ in the Osiris core.

of $^{239}\text{Pu}$ in the core at a 95% confidence level. This corresponds to a mass representing 10% of the total mass of fissioning elements in the Osiris core at equilibrium.

7. Conclusions

After 5 years of safe and stable operations, the Nucifer demonstrator performed a first reactor $\bar{\nu}_e$ detection with a sub sample of data corresponding to 145 and 106 days of reactor on and off data, respectively. This is the second shortest baseline detection ever made, $\sim 7$ m away from a reactor core, proving it possible to detect $\bar{\nu}_e$ even with such a low overburden and severe background conditions. This $\bar{\nu}_e$ detector prototype for nuclear reactor monitoring can be simply remotely operated, with a fully automated data analysis suite.

The next steps of the Nucifer project are still to be discussed and decided. A deployment at a commercial reactor is envisaged to fully demonstrate the concept of ”neutrinometry” for reactor safeguard measurements.

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