The Nucifer Experiment: Non-Proliferation with Reactor Antineutrinos

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Antineutrino from Nuclear Reactors

- Antineutrinos are produced in beta-decays of the fission products
- **Burnup**: as reactor fuel burns, the composition change
- Antineutrino rate varies with time and core composition

\[ N^\nu \sim \left[ 1 + f \left( \frac{M_U}{M_{Pu}} \right) \right] P_{th} \]

Any sudden change in the core composition causes a deviation of the normal curve of neutrino rate → can be detected

Detector of 1m³ @25 meters from a 3 GW PWR

5000 interactions/day expected

Refueling, 250 kg Pu replaced by fresh 235U
Antineutrino Detection and Background

A golden plated channel, IBD in LS:

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

**Prompt:**
- e+ releases energy in scintillator then annihilates
- \( E_{\nu} \approx E_{\text{prompt}} = E_{\text{scint}} + 2 \times 511 \text{keV} \)

**Delayed:** (\( \Delta t \approx 30 \mu\text{s for Gd} \))
- n thermalizes in few cm
- capture on Gd or H
- \( E_{\text{delayed}} \approx 8 \text{MeV for Gd} \)

**Background:**
- Radioactivity in PMT or surrounding material *(accidental)*
- Reactor background *(accidental)*
- Spallation neutrons *(correlated)*
Non-Proliferation: IAEA Interest

- Antineutrinos carry direct information from nuclear fuel and cannot be shielded.
- IAEA is interested in a "continuous unattended monitoring" of the nuclear material content through an intrusive-less technique to reduce the risk of proliferation of nuclear weapons.

**Detector Constraints:**
- Small size: 3m X 3m X 2.5m
- Do not induce significant additional safety risk to the power plant
- Remote and easy operation by inspectors

**Nucifer Challenges:**
- Effort to simplify the design/technology (synergy with Double Chooz) and run close to surface while keeping detector performances:
  - Attempt: 50% detection efficiency
- Proceed to the ‘industrialization’ of neutrino science.
Nucifer - Integration Stages

- **Integration tests** → Saclay ALS swallow depth lab (ongoing since 2010)

- **Deployment at a research reactor – Saclay Osiris (2011-12)**
  Site available at 7m from 70MW core, 15 m.w.e. overburden, ~680 antineutrino events/day expected
  Safety file is under review
  Background measurement completed → reactor induced rays implies an additional 10 cm lead shielding wall needed (under construction)

- **Deployment at a commercial reactor (2013).**
Nucifer Detector Module

Calibration pipe

16 8'PMT

Acrylic Buffer

Target: Teflon coated vessel filled with 0.85 m³ Gd loaded liquid scintillator

7 diodes LI system
Detector Overview: Components Against Background

10cm lead layer against gammas

15cm polyethylene shield against neutrons

Support structure

4π Muon Veto – plastic scintillator
Electronics & DAQ

- Electronics based on commercial modules, VME/NIM
- Absolute time recording for delay coincidence reconstruction
- Total charge recording for energy reconstruction
- Delayed charge recording for PSD studies
- Slow Control: temp., humidity, pressure, liquid level
- DAQ based on LabView, remote controlled.
- Dead time ~1% for 1.5kHz → **Background studies for low energy and fast calibration**
The comparison between the energy reconstruction (unshielded Nucifer detector), and simulations shows an excellent agreement → very good understanding of the detector response.
Calibration: Light Injection System

- 7 diodes LI system, running continuously at low frequency
- SPE spectra for PMT gain monitoring.
- Scintillator monitoring.

**LED patterns**

- Stability in time

**Diodes separately**

- Linearity:
  - Relative measurement
  - Residuals < 0.5% across whole energy range
Particle Discrimination: PSD

- Usually reactor closeness implies small overburden → important fast n background (correlated)

- **Expected signal to noise ratio approx. 0.25 (before any PSD cut)**

- Focus on Pulse Shape Discrimination (PSD) cut to extract clearly the neutrino signal (discriminate e+ signals from highly ionizing proton recoil induced by fast neutrons)

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![Graph showing pulse shape discrimination](image)

**\(^{252}\)Cf source, cell with Nucifer LS**
PSD Studies

- As expected, FoM ≈ 0.8. For 1% signal rejection → approx 90% background rejection!

- Qtail gate optimization is ongoing

[Graph showing Qtail/Qtot vs. p rejection with different signal and background distributions labeled as Tagged AmBe, BkG, and FoM cut. The graph includes a note indicating that σ_{e+} = σ_p by extrapolation.]
... and now something different ...
Revised prediction of reference reactor antineutrino spectra with +3% normalization shift


The synthesis of experiments at reactor-detector distances ≤ 100m → obs/pred. rate <1 @98.4% C.L.


See also Mike Shaevitz's talk in plenary on Tuesday.
Looking for new oscillation with $\lambda_{osc} \sim 1$ m with Nucifer@Osiris

- Compact reactor (57x57x60cm), compact detector (850l)
- Short baseline ($<L>=7$ m, $\sigma=0.3$ m) → oscillation not washed out
- Folding Nucifer Geant4 Monte Carlo detector response with anomaly best fit:

$$\Delta m^2 = 2.4 \text{ eV}^2 \text{ & } \sin^2(2\theta) = 0.15$$

Background not included
Conclusions

- Nucifer will provide unattended reactor monitoring as contribution to the nuclear safeguard activity.

- **Huge efforts for detector R&D.** Tests of the final configuration are ongoing.

- **First antineutrino event expected soon** (Osiris).

- **Perspectives for testing the 4th ν hypothesis.**
Вkp.
Distribution of the probability of issuing false alarms as a function of the probability of issuing valid alarms for the retrieval of a certain Pu mass considering two relative measurements with a statistics of 15 days each.