CORMORAD
COre Reactor MOnitorting by an Antineutrino Detector

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Genova- Italy
Antineutrinos are directly produced in fission ($\sim 10^{20} \bar{\nu}/s$)

Counts/day in organic scintillator detector (water-like)

$$10^6 \times V(m^3) \times P(GW) / D^2(m^2)$$

$\sim 6000 \text{ ev/d} \ @ \ 1m^3 \ P=3GW \ D=20m$

$\bar{\nu}$ flux proportional to power

Integrated counts allow to monitor the reactor power

$\bar{\nu}$ energy spectrum related to isotope decay

Antineutrino energy spectrum reveals the reactor core isotopic composition ($^{235}$U and $^{239}$Pu)
Why antineutrinos?

This is NOT the simplest way to monitor a reactor but ...

- independent on-line monitor of the reactor power
- the measurement is performed outside the core (safety issues) and does not affect the normal plant operations
- detector installation does not need any engineering work and can be done anytime in any plant
- antineutrino can not be shielded and are only sensitive to fission material
- direct measurement of core nuclear activity and fuel burn-up
- early detection of unauthorized plutonium production and subtraction (sensitivity down to 10th kg)
- On-line monitoring in case of disaster or decommissioning
How to detect antineutrinos?

**Inverse beta decay:** \( \nu p \rightarrow \beta^+ n \)

- **Reaction threshold** \( E_\nu = 1.8 \text{ MeV} \)
  - \( \rightarrow \) reactor-off contribution (long-life isotopes emitting low \( E_n \)) is negligible!
- **\( E_\nu \) (1.8 - 7 MeV)**

\[ \begin{align*}
E_\nu & \sim E_{e^+} \\
\beta^+ & \quad \text{few MeV positron: ionization} \\
& \quad e^+ e^- \rightarrow \gamma \gamma (2 \times 0.511 \text{ MeV}) \\
& \quad \text{prompt signal (t<1\( \mu \text{s} \))}
\end{align*} \]

\[ \begin{align*}
n & \quad \text{thermalization (np\rightarrow np)} \\
& \quad \text{capture on nucleus A} \\
& \quad \gamma \text{ cascade (} E_{\text{tot}} = 2-8 \text{ MeV)} \\
& \quad \text{delayed signal (} \tau \sim 5-100 \mu\text{s)}
\end{align*} \]

\[ \begin{align*}
\ast & \quad \text{energy deposition} \\
\ast & \quad \text{time interval}
\end{align*} \]
Does it work?

Sandia National Laboratory antineutrino detector (SONGS1) S.Onofre (Ca) 3.5 GW commercial power plant

Daily power monitoring using only antineutrinos

```
<table>
<thead>
<tr>
<th>Day</th>
<th>Reactor to 15%</th>
<th>Start ramp to 100%</th>
<th>Reactor trips</th>
<th>Start ramp to 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/12/2004</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/14/2004</td>
<td>210</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/16/2004</td>
<td>220</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/18/2004</td>
<td>230</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/20/2004</td>
<td>240</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

= reported thermal power

```

Detection efficiency (10.7±1.5) %

Preliminary indication of Burnup effect

```
<table>
<thead>
<tr>
<th>Date</th>
<th>Counts per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun '05</td>
<td>500</td>
</tr>
<tr>
<td>Jul '05</td>
<td>550</td>
</tr>
<tr>
<td>Aug '05</td>
<td>600</td>
</tr>
<tr>
<td>Sep '05</td>
<td>550</td>
</tr>
<tr>
<td>Oct '05</td>
<td>500</td>
</tr>
<tr>
<td>Nov '05</td>
<td>450</td>
</tr>
<tr>
<td>Dec '05</td>
<td>400</td>
</tr>
</tbody>
</table>

```

Predicted

Data

Fit to data

5) CORMORAD - COre Reactor MOntoRing by an Antineutrino Detector

M.Battaglieri - INFN Genova
CORMORAD
CORe MOntoRing by Antineutrino Detection

- Active volume: $\sim 1\text{m}^3$
- N scintillator bars wrapped in 12.5µm Mylar-Gd foils
- Bar sizes: 3-7 x 3-7 x 100-150 cm$^3$
- 2”-3” PMT on Each side
- 10-15% of produced light collected
- minimum light attenuation
  plastic scintillator attenuation length
  $\sim 300\text{cm}@425\text{nm}$
- ADC and TDC read-out

☆ Project part of the INFN-E strategic plan and in the INFN-Ansaldo agreement
Reaction selection and bg rejection

**Signal** \( \nu p \rightarrow \beta^+ n \)

<table>
<thead>
<tr>
<th>Prompt signal ((&lt;1\mu s))</th>
<th>Delayed signal (1-100 (\mu s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>antineutrino interact with H in plastic</td>
<td>n thermalizes (np(\rightarrow)np)</td>
</tr>
<tr>
<td>positron releases energy within a cell</td>
<td>tenth of cm ((&gt;) cell size)</td>
</tr>
<tr>
<td>Then annihilates</td>
<td>capture on A</td>
</tr>
<tr>
<td>two gammas mainly interact via</td>
<td>delayed signal ((\tau) 5-100 (\mu s))</td>
</tr>
<tr>
<td>Compton scattering</td>
<td>(E_{\text{Delayed}} = E_{\text{elastic}} + 7-8) MeV</td>
</tr>
<tr>
<td>(E_\nu \propto E_{\text{Prompt}} = E_{\text{ion}} + 2 \times 0.511) MeV</td>
<td>High hit multiplicity</td>
</tr>
<tr>
<td>(N_{\text{hit}} &gt; 2)</td>
<td></td>
</tr>
</tbody>
</table>

**Background**

- Atmospheric and solar \(\rightarrow\) negligible
- Cosmic muons \(\rightarrow\) tracked and rejected in off-line analysis
- Residual radioactivity in PMTs and surrounding material \(\rightarrow\) trigger optimization
- Spallation and cosmic neutron
  - slowed down by elastic np scattering
  - p fast signal (similar to e+)
  - n delayed signal (as in inverse \(\beta\) decay)
  \(\rightarrow\) same time-coincidence signature
  \(\rightarrow\) rejected by using hit multiplicity
  \(\rightarrow\) need segmented detector!
- Reactor background
  - thermal neutrons
  - few MeV gammas from n activation
  \(\rightarrow\) random coincidences depending on the single hit rates
  \(\rightarrow\) need shielding
CORMORAD prototype
CORMORINO
scale \((1:3)^3 \sim 3\% \ m^3\)

Prototype cell

- 4 30x5x5 cm\(^3\) NE110 bars
- 1 5x10x10 cm\(^3\) NE110 block
- 12.5 \(\mu\)m Gd foils wrapping

Size: 40 x 30 x 30 cm\(^3\)

Light read-out:
- 18 Photonis XP2312 3” PMTs
CORMORINO @ Cernavoda (Ro)

Test run in Cernavoda (Ro) SNN nuclear power plant during outage/restart in May 09

2 GW reactor off/on for maintenance
~30m far from the reactor core
In-truck movable detector

Test Goals

- In-situ measurement
- Experimental set-up optimization
- Background rates
- Reactor On/Off change
- MC validation
- Data analysis optimization

Test runs

- Reactor off
  ~1 week; natural bg
- Reactor on
  ~3 weeks; max power
- Reactor on + B-shield
  ~2 weeks; bg nature

Remote controlled using a modem/phone connection (VM/HV)
Smooth running
Cosmic ray runs for calibration
Event Rate and plant power

Recorded DAQ rate

Reactor restart

Reactor ON: full power

Reactor ON: with B-shield

Reactor OFF

Reactor power (from SNN)

Rate dominated by bg

Expected anti-nu rate: $2.5 \times 10^{-5}$ Hz

Measured rate (Reac-ON): 8 Hz

Rate atteso di antineutrini: $2.5 \times 10^{-5}$ Hz

Rate totale a reattore acceso misurato: 8 Hz

Provided by SNN

Calculated from DAQ rate assuming:

$$R_{\text{double}} = 2 \tau R_{\text{single}}$$

Reac-OFF: natural bg, cosmic $\mu$, $n$

Reac-On: reactor $\gamma$ and $n$
Reactor OFF
(cosmic $\mu$ and n)

Time-correlated neutron rate: \((1.2 \pm 0.1) \times 10^{-2} \text{ Hz}\)

\[T_{dl} - T_{pr} = p_1 e^{-t/\tau} + p_3\]
\[\tau \sim 40 \, \mu\text{s}\]
Cosmic neutrons (GEANT4 simulations)

Generated spectrum

Prompt E spectrum

Delayed E spectrum

- Cernavoda Reactor OFF
- Genova OPEN-AIR
- GEANT4 sim (x 0.5)
- GEANT4 sim (x 0.3)
Reactor ON
(\(\gamma\) and \(n\))

Reactor ON

- Increased rate
- Increased uncorrelated component

Background from the reactor

<table>
<thead>
<tr>
<th>ID</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100000</td>
<td>154.4</td>
<td>97.02</td>
</tr>
</tbody>
</table>

\[ T_{dl} - T_{pr} = p_1 e^{-t/\tau} + p_3 \]

Reactor OFF

\[ T_{dl} - T_{pr} \approx \text{cost} \]

- Time-uncorrelated \(\rightarrow\) gamma from reactor
- Time correlated (on top of cosmic \(n\)) \(\rightarrow\) neutrons from reactor
Cernavoda CANDU simulations

neutron and gamma fluxes were generated with a realistic core description (but not a CANDU)! and transported to the CORMORINO position

Full core and surrounding buildings geometry implemented in MCNPX framework

Ansaldo SpA
Direct & activation gammas (sim/data)

Photon rate ($R_{\text{double}}$)

$R_{\text{double}} = 2 \tau R_{\text{single}} R_{\text{single}}$

w and w/o B-shield (15 cm thickness, in front of the detector)

Unshiled: 68.3 ± 0.1 Hz
Shielded: 47.2 ± 0.1 Hz
Shileded/Unshielded ~ 30% (~27% from GEANT SIM)

Good agreement data/sim for spectra and absolute rates

Simulated photon spectrum

$^{16}$O activation photons

Energy spectrum: MCNPX simulation
starting from a realistic core/materials description + normalization to a dose measurement close to the core

Angular distribution: straight line from reactor core

Activation: mainly from cooling water

$n + ^{16}$O $\rightarrow$ p + $^{16}$N
$^{16}$N $\rightarrow$ $^{16}$O* + e$^+$ + anti-nu
$^{16}$O* $\rightarrow$ $^{16}$O + $\gamma$ (6.13 MeV 92%)
Neutrons from reactor (sim/data)

After cosmic-n subtraction from the correlated part of the time spectrum (real double coincidences!) something remains ...

Neutron rates

w and w/o B-shiled (15 cm thikness, in front of the detector)

Unshielded: (2.5 +/- 0.2) \(10^{-2}\) Hz

Shielded: (1.1 +/- 0.4) \(10^{-2}\) Hz

Shielded/Unshielded ~ 45% (~30% from GEANT SIM)

Reasonable agreement data/sim for relative rates

★ No absolute normalization in sim

★ We compared B-shield effect in data/sim

Neutrons produced by the reactor activity are a correlated component of the spectrum, with the same signature of the anti-nu signal

Needed to be shielded!

Simulated neutron spectrum

GEANT4 simulation

Energy spectrum: MCNPX simulation starting from a realistic core/materials description in the range \(10^{-2} < E < 10\) MeV

Angular distribution: straight line from reactor core (it may be wrong)
Rates
as seen or expected from CORMORINO with optimized analysis cuts

<table>
<thead>
<tr>
<th>particle</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-nu</td>
<td>$(1.1 \pm 0.1) \times 10^{-5}$</td>
</tr>
<tr>
<td>gamma (from reactor)</td>
<td>$(7.8 \pm 0.1) \times 10^{-3}$</td>
</tr>
<tr>
<td>neutron (from reactor)</td>
<td>$(3.1 \pm 0.5) \times 10^{-3}$</td>
</tr>
<tr>
<td>neutron (cosmic)</td>
<td>$(2.3 \pm 0.2) \times 10^{-3}$</td>
</tr>
</tbody>
</table>

It is not possible to extract from these data the anti-nu signal ... but this was only a prototype!

Detection strategy
towards a full-scale detector

1) Increase anti-nu rate by loosing DAQ trigger and analysis conditions
   → full size ~1m$^3$ detector
2) Reduce to negligible value any reactor-correlated bg
   → passive screens
3) Reduce as much as possible cosmic n bg
   → passive screens
CORMORAD - CORE Reactor MONItorRing by an Antineutrino Detector

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Size: 130 x 98 x 98 cm³
14x14 plastic scint bars
12.5 μm Gd foils wrapping
98 PMTs readout

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<tr>
<th>particle</th>
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<tbody>
<tr>
<td>Anti-nu</td>
<td>(2.5 ± 0.5) $10^{-2}$</td>
</tr>
<tr>
<td>gamma (from reactor)</td>
<td>(3 ± 1) $10^{-3}$</td>
</tr>
<tr>
<td>neutron (from reactor)</td>
<td>(2.2 ± 0.7) $10^{-5}$</td>
</tr>
<tr>
<td>neutron (cosmic)</td>
<td>(5.8 ± 0.6) $10^{-2}$</td>
</tr>
</tbody>
</table>
Size: 130 x 98 x 98 cm³
☆ 14x14 plastic scint bars
☆ 12.5 µm Gd foils wrapping
☆ 98 PMTs readout

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<tr>
<td>neutron (from reactor)</td>
<td>(2.2 ± 0.7) 10^-5</td>
</tr>
<tr>
<td>neutron (cosmic)</td>
<td>(5.8 ± 0.6) 10^-2</td>
</tr>
</tbody>
</table>

~ 90 anti-nu/h

3σ separation: in 30'
δP/P~20%: in 20'

Iron + B-loaded paraffin + lead 3.41 + 0.59 t +2.89 t
Lead (reactor gammas) 4.76 t
B-loaded paraffin (reactor neutron) 0.81 t
Detector 1.48 t

13.9 t total still fits container load
Size: 130 x 98 x 98 cm³

- 14x14 plastic scint bars
- 12.5 μm Gd foils wrapping
- 98 PMTs readout

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<thead>
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<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-nu</td>
<td>((2.5 \pm 0.5) \times 10^{-2})</td>
</tr>
<tr>
<td>gamma (from reactor)</td>
<td>((3 \pm 1) \times 10^{-3})</td>
</tr>
<tr>
<td>neutron (from reactor)</td>
<td>((2.2 \pm 0.7) \times 10^{-5})</td>
</tr>
<tr>
<td>neutron (cosmic)</td>
<td>((5.8 \pm 0.6) \times 10^{-2})</td>
</tr>
</tbody>
</table>

\(~ 90\) anti-nu/h

negligible

3σ separation: \(\delta P/P \sim 20\%: \) in 30'
\(\delta P/P \sim 20\%: \) in 20'

B-loaded paraffin + lead  0.59 t +2.89 t
Lead (reactor gammas)     4.76 t
B-loaded paraffin (reactor neutron) 0.81 t
Detector                  1.48 t

10.5 t total
better fits container load
Ansaldo + JLab LAC (2m³)

Reuse of JLab/LAC calorimeter

- Size: 200 x 100 x 100 cm³
- 600 plastic scint bars (grouped in 6)
- 12.5 µm Gd foils wrapping
- 220 PMTs readout
- Same Fe/B/Lead shielding

<table>
<thead>
<tr>
<th>particle</th>
<th>eff %</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-nu</td>
<td>80</td>
<td>(4.4 ± 0.5) 10⁻²</td>
</tr>
<tr>
<td>gamma (from reactor)</td>
<td>0.001</td>
<td>(4 ± 1) 10⁻³</td>
</tr>
<tr>
<td>neutron (from reactor)</td>
<td>0.001</td>
<td>(7 ± 2) 10⁻⁴</td>
</tr>
<tr>
<td>neutron (cosmic)</td>
<td>3</td>
<td>(5.1 ± 0.4) 10⁻²</td>
</tr>
</tbody>
</table>

~ 160 anti-nu/h

3σ separation: in 10'
δP/P~ 20%: in 30'
δP/P~ % (via γ): in ''

Total weight ~ 21t compatible with a ISO 20' (2.3x2.3x5.8m³) container
<table>
<thead>
<tr>
<th>Voce del preventivo</th>
<th>Costo costruzione ex-novo (euro)</th>
<th>Costo costruzione da LAC (euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rivelatore</td>
<td>605000</td>
<td>80000</td>
</tr>
<tr>
<td>Veti passivi</td>
<td>85000</td>
<td>70000</td>
</tr>
<tr>
<td>Lavorazione</td>
<td>15000</td>
<td>70000</td>
</tr>
<tr>
<td>Elettronica</td>
<td>250000</td>
<td>165000</td>
</tr>
<tr>
<td><strong>Totale</strong></td>
<td><strong>955000</strong></td>
<td><strong>385000</strong></td>
</tr>
<tr>
<td><strong>Totale + contingenza (10%)</strong></td>
<td><strong>1050000</strong></td>
<td><strong>425000</strong></td>
</tr>
</tbody>
</table>

**Personale:**
- 2 assegni di ricerca x 2 anni = 85k
- 1 CTER x 1 anno = 30k

**Bibliografia:**
- G. Firpo *Studio di un rivelatore per la misura di anti-nu da centrale nucleare* (tesi di Laurea)
- L. Faure *Calibrazione e misura della risposta di un rivelatore di anti-nu da reattore* (tesi di Laurea)
- L. Ficini et al. *Preventivo per la realizzazione di un prototipo di CORMORAD di volume 2m³* (report INFN)
- L. Ficini et al. *Study and optimization of CORMORAD detector* (report INFN)
- G. Firpo *CORMORAD - Stato di maturità del progetto e prospettive future* (report Ansaldo)
- Presentazione a conferenze e workshop internazionali (Battaglieri, Firpo, Ficini)