Angra Neutrino Project: Safeguards Applications

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Outline

- Neutrinos and Non-proliferation

- Monitoring Nuclear Activity with Antineutrinos
  - Main concepts
  - Previous experiments

- ANGRA Neutrino Project
  - The Brazilian nuclear complex: Angra dos Reis
  - Detector design
  - Institutional relationship

- Conclusions
Neutrinos & Non-proliferation

- ~438 reactors worldwide:
  The International Atomic Energy Agency (IAEA) inspects nuclear facilities under safeguards agreements.

- ~200kg plutonium produced each reactor cycle (~1.5 years)
  ~90 tons of plutonium produced every year worldwide
  IAEA verify that fissile materials are used for civil appliances.

- IAEA is the verification authority:
  Treaty on the Non-Proliferation of Nuclear Weapons (NPT):
Non-proliferation in Latin-America: ABACC interest and Support

- **Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC):**
  Binational agency created by the governments of Brazil and Argentina (1991), responsible for verifying the peaceful use of nuclear materials that could be used, either directly or indirectly, for the manufacture of weapons of mass destruction.
Why the interest in antineutrino detectors?

- Search for new methods on safeguards verification

- Antineutrinos can not be shielded and are produced in very large amounts ($\sim 10^{20}$ anus/s)

- Antineutrinos produced in reactors can reveal fissile composition of nuclear fuel

- Non-intrusive: Remotely monitor real-time reactor state: thermal power and fissioning material
Non intrusive method to check reactor activity

$^{238}_{92}U + n \rightarrow ^{239}_{92}U \quad \text{23 min} \quad ^{239}_{93}Np \quad \text{2.3 d} \quad ^{239}_{94}Pu$

Plutonium production chain

Detection process

$\bar{\nu}_e + p \rightarrow e^+ + n$
Previous experiments:

Reactor Thermal Power and Antineutrino flux

- Relation between delivered thermal power and antineutrino flux

\[ N_\nu = \gamma \cdot (1 + k) \cdot P_{th} \]

Dependence on detector features

Dependence on fuel composition
Reactor power x neutrino flux
Measuring of power production by neutrino method

Reactor power in % from nominal value (1375 MW)
Reactor power x neutrino flux

Number of antineutrinos
Composition of the Fuel

- The effect of the composition of the fuel is more strongly manifested in the antineutrino energy spectrum.

\[ 1 - r_{\text{beg}/\text{end}} \]

Rovno 1988-1990

Expected from ILL spectra

\[ E_{\nu}, \text{MeV} \]
Antineutrino Emission Spectrum from Reactor Fuel

<table>
<thead>
<tr>
<th></th>
<th>Mean energy per fission (MeV)</th>
<th>Start of Cycle</th>
<th>End of Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}$U</td>
<td>201.7 ± 0.6</td>
<td>60.5%</td>
<td>45.0%</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>205.0 ± 0.9</td>
<td>7.7%</td>
<td>8.3%</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>210.0 ± 0.9</td>
<td>27.2%</td>
<td>38.8%</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>212.4 ± 1.0</td>
<td>4.6%</td>
<td>7.9%</td>
</tr>
</tbody>
</table>

Antineutrino spectra measured by ILL group 1983-1989
Burn-up effect on fuel composition
New parameterization of Spectra:
P. Huber, T. Schwetz hep-ph/0407026

$\phi_\ell(E_\nu) = \exp\left( \sum_{k=1}^{K_\ell} a_{\ell k} E_\nu^{k-1} \right)$

<table>
<thead>
<tr>
<th>$\ell = ^{235}\text{U}$</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$</td>
<td>$a_{\ell k}$</td>
<td>$\delta a_{\ell k}$</td>
</tr>
<tr>
<td>1</td>
<td>$3.519 \cdot 10^6$</td>
<td>$7.26 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>2</td>
<td>$-3.517 \cdot 10^6$</td>
<td>$8.51 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>3</td>
<td>$1.505 \cdot 10^6$</td>
<td>$4.06 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>4</td>
<td>$-4.471 \cdot 10^{-1}$</td>
<td>$8.90 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>5</td>
<td>$5.004 \cdot 10^{-2}$</td>
<td>$9.34 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>6</td>
<td>$-2.303 \cdot 10^{-3}$</td>
<td>$3.77 \cdot 10^{-4}$</td>
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<table>
<thead>
<tr>
<th>$\ell = ^{239}\text{Pu}$</th>
<th></th>
<th></th>
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<tr>
<td>$k$</td>
<td>$a_{\ell k}$</td>
<td>$\delta a_{\ell k}$</td>
</tr>
<tr>
<td>1</td>
<td>$2.560 \cdot 10^6$</td>
<td>$4.01 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>2</td>
<td>$-2.654 \cdot 10^6$</td>
<td>$5.58 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>3</td>
<td>$1.256 \cdot 10^6$</td>
<td>$2.91 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>4</td>
<td>$-3.617 \cdot 10^{-1}$</td>
<td>$7.17 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>5</td>
<td>$4.547 \cdot 10^{-2}$</td>
<td>$8.37 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>6</td>
<td>$-2.143 \cdot 10^{-3}$</td>
<td>$3.73 \cdot 10^{-4}$</td>
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</table>

<table>
<thead>
<tr>
<th>$\ell = ^{241}\text{Pu}$</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$</td>
<td>$a_{\ell k}$</td>
<td>$\delta a_{\ell k}$</td>
</tr>
<tr>
<td>1</td>
<td>$1.457 \cdot 10^6$</td>
<td>$3.23 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>2</td>
<td>$-1.638 \cdot 10^6$</td>
<td>$4.31 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>3</td>
<td>$4.130 \cdot 10^{-1}$</td>
<td>$2.15 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>4</td>
<td>$-1.423 \cdot 10^{-1}$</td>
<td>$5.02 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>5</td>
<td>$1.860 \cdot 10^{-2}$</td>
<td>$5.54 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>6</td>
<td>$-9.220 \cdot 10^{-4}$</td>
<td>$2.33 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>
Fuel composition

Virtual experiment:

Simulated spectrum:
- \(a_5 = 0.614,\)
- \(a_9 = 0.274,\)
- \(a_8 = 0.074,\)
- \(a_1 = 0.038,\)

Fitting spectrum:
- \(a_5 = 0.631 \pm 10\%,\)
- \(a_9 = 0.260,\)
- \(a_8 = 0.074,\)
- \(a_1 = 0.035,\)
Main Requirements for Safeguards Antineutrino Detectors:

Workshop on the ANGRA detector design
(CBPF - May 16-19, 2006, Rio de Janeiro - BR)

- Prescriptions

Discussions ↔ Agreements

Main requirements for verification detectors
Deployment strategies
Workshop Prescriptions: SANDS & ANGRA approaches:

- **SANDS (+)**
  - Simple
  - Robust
  - Well known technologies
  - Easy to be adapted in a compact design

- **SANDS (-)**
  - Restricted performance

- **ANGRA (+)**
  - High performance
  - State-of-Art of antineutrino detection (Chooz, KamLAND)
  - Foot-print: at least the same as current experiments

- **ANGRA (-)**
  - Complex
  - Development Stage
Workshop Prescriptions: SANDS & ANGRA synthesis

- SANDS (++)
- ANGRA (+)

Coordinate Effort: following 2 different approaches

The “Ideal Detector”:  
- High Performance  
- Robust  
- Compact  
- ...

Faster and Cheaper Development !!!
The ANGRA Neutrino Project

- Safeguards tools development
- Neutrino oscillations measurements?
Safeguards Detector site:

Selected Places for the SAFEGUARDS DETECTOR
**Very Near Detector: Standard 3 volumes Design**

A) **Target** \((R_1=0.5\,\text{m}; \, h_1=1.3\,\text{m})\)
   - Acrylic vessel + lqd scintillator(+Gd)

B) **Gamma-Catcher** \((R_2=0.8\,\text{m}; \, h_2=1.9\,\text{m})\)
   - Acrylic vessel + lqd scintillator

C) **Buffer** \((R_3=1.4\,\text{m}; \, h_3=3.10\,\text{m})\)
   - Steel vessel + mineral oil

D) **Vertical Tiles of Veto System**

E) **X-Y Horizontal Tiles of Veto System**
   - Plastic scintillator padles

above and under the external steel cylinder:
muon tracking through the detector
**Expected Signal & Background**

**Cylindrical detector dimensions**

$R_3 = 1.40\text{m}; \ H=3.10\text{m} \ target=1\text{ton}$

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Signal (day)</th>
<th>Depth (mwe)</th>
<th>Muons (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1270</td>
<td>755</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>933</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>714</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>564</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>457</td>
<td>110</td>
<td></td>
</tr>
</tbody>
</table>
Angra Project: Present Status

- Meeting September 05, 2006 with Eletronuclear representatives to define next steps.

- Detailed project under way to be presented to the Minister of Science and Technology and to FAPESP.

- Start to test components at CBPF and UNICAMP: (phototubes + VME electronics)
Phase I:  
Setup infrastructure at the Angra site:

- 20’ container near the reactor building
- Measurement of local muon flux:
  - Cerenkov detector (Auger test tank)
- Muon telescope (4 Minos type scintillator planes)
- Measurement of radioactive background: (rocks and sand)
Phase II: Deploy LVD tank

- 1 ton gadolinium doped liquid scintillator tank
- test signal + background
- Tests with Californium source
- Final site selection for underground laboratory
Phase II: Electronics & DAQ

- **Front-end electronics**
  - input buffer + amplifier/shaper
  - To ADC: + line driver
  - To Trigger system: + comparator

- **Data Acquisition (DAQ)**
  - VME-based
  - off-the-shelf high-performance devices (ADCs, FPGAs, FIFOs)
  - two sub-systems: neutrino signal / VETO
  - Neutrino: ~ 120 input channels sampled at 250Msps / 10-bit resolution
  - VETO: ~ 110 LVDS signals to a large/fast FPGA (Stratix II)
Phase III:

- Construction of the underground laboratory.
- Construction of three volume detector and muon veto.
- Deployment of detector parts, integration and commissioning.
Conclusions

- Previous experiments demonstrate a good capability of using Antineutrinos for Nuclear reactor distant monitoring.
- High precision thermal power and fuel composition measurement can be achieved.
- Better accuracy for antineutrino spectra of U & Pu is needed.
- Good opportunity develop experimental neutrino physics in Brazil and to contribute to new safeguards techniques.
- Short baseline Neutrino Oscillations: collaboration with Double Chooz? High precision experiment around 2013?
why not an international project?

Thank you!

janjos@cbpf.br
Phase IV (2013?):
high precision measurement of $\theta_{13}$?

“Morro do Frade”

- **Near (reference) detector:**
  - 50 ton detector (7.2 m dia)
  - 300 m from core
  - 250 m.w.e.

- **Far (oscillation) detector:**
  - 500 tons (12.5 m dia)
  - 1500 m from core
  - 2000 m.w.e.
    (under “Frade” peak)

- **Very Near detector:**
  - 1 ton prototype project
  - < 50m of reactor core

- **Detector Construction**
  - Standard 3 volume design
## Reactor ν Experiment Physics

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Optimistic start date</th>
<th>GW-t-yr (yr)</th>
<th>90% CL Sin²2θ&lt;sub&gt;13&lt;/sub&gt; sensitivity</th>
<th>for ∆m&lt;sup&gt;2&lt;/sup&gt; (10&lt;sup&gt;-3&lt;/sup&gt; eV&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>efficiencies</th>
<th>Far event rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANGRA</td>
<td>2013(full)</td>
<td>3900(1)</td>
<td>0.0070</td>
<td>2.5</td>
<td>0.8×0.9</td>
<td>350,000/yr</td>
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<tr>
<td></td>
<td></td>
<td>9000(3)</td>
<td>0.0060</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15000(5)</td>
<td>0.0055</td>
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<tr>
<td>Braidwood</td>
<td>2010</td>
<td>845(1)</td>
<td>0.007</td>
<td>2.5</td>
<td>0.75</td>
<td>41,000/yr</td>
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<tr>
<td></td>
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<td>2535(3)</td>
<td>0.005</td>
<td></td>
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<td></td>
<td></td>
<td>7605(9)</td>
<td>0.0035</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daya Bay</td>
<td>08(fast)</td>
<td>3700(3)</td>
<td>0.008</td>
<td>2.5</td>
<td>0.75×0.83</td>
<td>70,000/yr</td>
</tr>
<tr>
<td></td>
<td>09(full)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>110,000/yr</td>
</tr>
<tr>
<td>Double</td>
<td>Oct 07(far)</td>
<td>29(1)</td>
<td>0.08</td>
<td>2.5</td>
<td>0.8×0.9</td>
<td>15,000/yr</td>
</tr>
<tr>
<td>Chooz</td>
<td>Oct 08(near)</td>
<td>29(1+1)</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>80(1+3)</td>
<td>0.025</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KASKA</td>
<td>Mar 09</td>
<td>493(3)</td>
<td>0.015</td>
<td>2.5</td>
<td>0.8×0.88</td>
<td>24,000/yr</td>
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<tr>
<td>RENO</td>
<td>Late 09</td>
<td>340(1)</td>
<td>0.03</td>
<td>2.0</td>
<td>0.8</td>
<td>18,000/yr</td>
</tr>
</tbody>
</table>
ANGRA II:
ν Survival Probability
$E_{\text{min}} = 1.8 \text{ MeV}; \quad 95\% @ 5 \text{ MeV} \text{ (far detector)}$
Sensitivity studies

- **d/D:** detectors
- **b/B:** bin (energy)
- **capital:** correlated
- **small:** uncorrelated

Expected Sensitivity at 90% for 6000 GW·t·yr

- $L_{\text{near}} = 0.3\text{km}$, $L_{\text{far}} = 1.5\text{km}$
- $V_{\text{near}} / V_{\text{far}} = 0.1$

$\Delta m_{13}^2 (eV^2)$

- $\sigma_{DB}=1.0\%$, $\sigma_{Db}=1.0\%$, $\sigma_{db}=0.5\%$, $\sigma_{dB}=0.2\%$
- $\sigma_{DB}=1.0\%$, $\sigma_{Db}=1.0\%$, $\sigma_{db}=0.1\%$, $\sigma_{dB}=0.2\%$
- No Systematic Errors

$\sin^2 2\theta_{13}$
Sensitivity to Sterile Neutrinos

\[ \Delta m^2 (\text{eV}^2) \]

\[ 90\% \text{ CL (1 d.o.f.)} \]

4.5 GW, 2 yr
\[ V_1 = 1 \text{ t}, \ V_2 = 500 \text{ t} \]
\[ L_1 = 66 \text{ m}, \ L_2 = 1.5 \text{ km} \]

Bugey

conservative sys. error
optimistic sys. error
Antineutrino Detector: Basic concepts

Central volume (target) scintillator + Gd (~0.5 g/l)

Externol volume Gamma catcher (liquid scintillator)

Photomultiplier tubes

Muon veto (plastic scintillator)

A 1-7 MeV positron
A few keV neutron
Mean time window 28 µs
Phase I:

- Measurement of radioactive background (rocks and sand)