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Monitoring Nuclear Reactors with Antineutrino Detectors: the ANGRA Project

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Abstract. We present the status of the ANGRA Neutrino project, aimed at developing an antineutrino detector for monitoring nuclear reactor activity. The Angra experiment will be deployed at the Brazilian nuclear power plant Angra II. A water Cherenkov detector of one ton target will be placed in a commercial container just outside the reactor containment, about 25 m from the reactor core. The 4 GW thermal power of the Angra II reactor will provide a few thousand antineutrino interactions per day. The main challenge of the experiment will be to overcome the very high cosmic ray induced background at sea level, consisting mainly of muons, neutrons, gammas and electrons. The event analysis strategy to overcome the large background is being developed and will be described.

1. Introduction

Nuclear reactors are intense source of antineutrinos and the thermal power released in the fission process is directly related to the emitted antineutrino flux. As antineutrinos interact very weakly with matter and escape the reactor containment without any significant change in their number, measuring the antineutrino flux can provide quasi real time information on the reactor status (on/off) and thermal power. Indeed it has been shown that antineutrino detectors have the potential capability to monitor nuclear reactors' operational status and power level in quasi real time from outside the reactor containment [1]. This unique characteristic makes such detectors a powerful candidate to become in the near future a new tool for monitoring reactor facilities under the regime of nuclear safeguards.

The signature of antineutrino interactions is provided by the detection of the secondary particles in the inverse beta-decay (IBD) reaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n \cdot$$

The positron generates a prompt signal and the delayed detection of gammas from the neutron capture after thermalization will give a second signal. The trigger for the antineutrino detection is provided by the delayed coincidence of these two signals in a characteristic time window of 100 μs.

By measuring the neutrino flux we can directly estimate the thermal power produced in the reactor core. The neutrino event rate N_ν at the detector and the thermal power P_{th} are related by

$$N_\nu = \gamma(1+k)P_{th} \quad (1)$$

where γ is a constant which depends on the characteristics of the detector whereas k is a constant which depends on the time evolution of the fuel composition. Furthermore as the amount of fissile elements change during the burn up of the nuclear fuel and each fissile isotope has a characteristic antineutrino energy spectrum, measuring the antineutrino energy spectrum escaping the reactor can give also information on the composition of the nuclear fuel.

The goal of the Angra Neutrino Project [2] is to develop an antineutrino detector aimed at monitoring nuclear reactor activity for the future incorporation of antineutrino detection technology into nuclear safeguards. The experiment will take place at the Angra II reactor in the Brazilian nuclear complex Almirante Álvaro Alberto, located near the city of Angra dos Reis, about 200 km South of Rio de Janeiro.

2. The Angra project: present status

After an agreement with Eletronuclear, the company operating the power plant, we have been authorized to deploy a neutrino laboratory in a commercial container placed next to the Angra II containment building, about 25 m from the reactor core, as shown in Fig. 1. Due to the Eletronuclear safety rules, the construction of a shaft to bury the detector and protect it from the cosmic ray background and the use of liquid scintillator near the reactor were not allowed. On the other hand an easily deployable detector with reduced footprint was the design feature recommended in the final report of the Focused Workshop on Antineutrino Detection for Safeguards Applications held in October 2008 at the International Atomic Energy Agency (IAEA) headquarters in Vienna [3]. In order to comply with this recommendation we have adopted a very challenging design: a 1 ton water Cherenkov detector running in a container above ground. The main challenge will be to overcome the large background induced by cosmic rays at ground level.

Fig. 1. Photo of the neutrino laboratory just outside the Angra II reactor containment building.

2.1 Detector Design

The adopted detector design is an assembly of three subsystems: i) the central detector, based on the water Cherenkov technique; ii) an external 30 cm passive shield composed of Boron loaded water tanks to protect the inner parts from cosmic ray induced neutrons and low energy external background as natural radioactivity; iii) a muon veto with 98% minimum efficiency placed in the outer most detector layer, based on extruded plastic scintillator strips and wavelength shifting optical fibers read by multi-anode PMTs.

The central detector consists of a 25 cm neutron shield surrounding the target volume and a 1 ton central target both filled with a 0.2% Gadolinium loaded water. The Gadolinium addition enhances the neutron signal due to the higher energy of the de-excitation gammas (Σ = 8 MeV) and reduces the average time for neutron capture to ~ 30 μs for this Gd concentration. The target mass provides a neutrino interaction rate of ~ 5.3×10^3 events per day considering a distance of 25 m to the reactor core and 4 GW of reactor power.

A sketch of the central detector is shown in Fig. 2a emphasizing the distribution of the Hamamatsu R5912 PMTs in four inner walls of the Cherenkov tank. In Fig.2b we show the number of photo-electrons (p.e.) detected as a function of the number of PMTs for a 2 MeV positron generated at the center of the detector. Based on this simulation we fixed in 40 the total number of PMTs, most of them concentrated in the top and bottom walls of the target box.

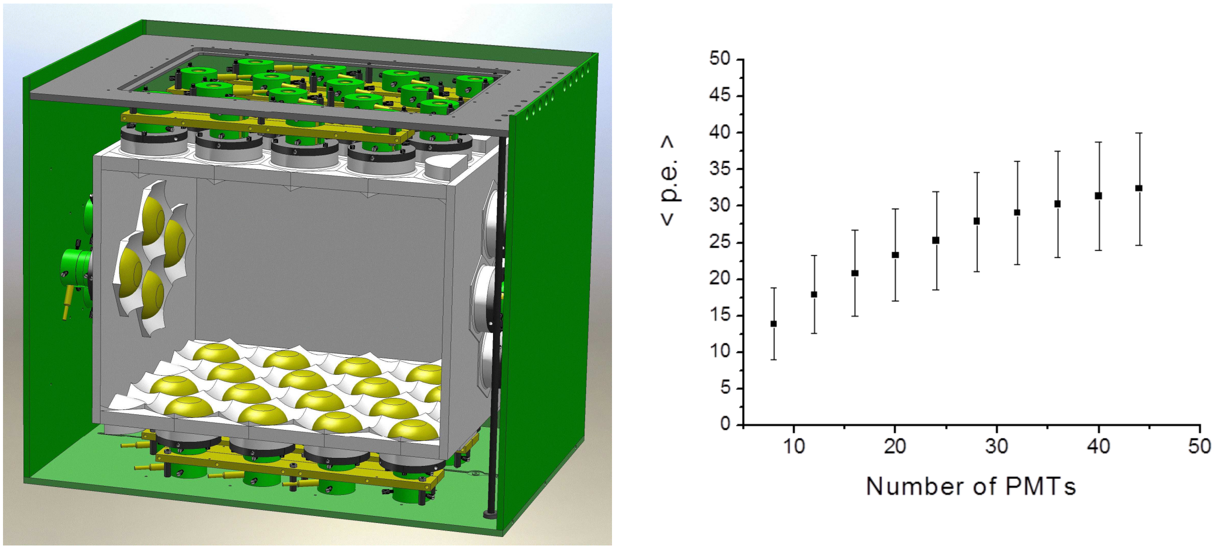

Fig. 2. a) *Sketch of the Angra Water Cherenkov detector. The external tank dimensions are 2.0 m long, 1.4 m wide and 1.6 m height with reflective (95%) inner walls. b) Number of photo-electrons collected as a function of the number of PMTs for a 2 MeV positron generated at the center of the detector*

2.2 Front-end Electronics

The front-end electronics consists of a wave form digitizer to measure the charge deposited by particles in the target volume and a TDC to give the relative time of the pulses in each PMT. An 8 channel 6U VME standard module has already been developed and is currently being used for PMT tests in different setups, including single-photo-electron measurements. The circuit is based on a low-noise, FET-input operational amplifier and includes stages for amplification, shaping and filtering. A simplified block diagram of the Neutrino DAQ module is presented in Fig. 3. Each analog-to-digital conversion channel is implemented using a 12-bit multi-stage pipeline ADC able to sample the input signal at 125 MHz. By defining a resolution of 10 bits and a dynamic range of 2 Vpp, a voltage resolution around 2 mV is achieved, which is expected to cover the required resolution in energy (considering 4 mV per p.e.). For high-precision measurement of time between pulses an 8-channel Time-to-Digital Converter (TDC) chip has been selected. The TDC presents a resolution of 81 ps and is able to measure pulses in a range of 9.8 μs. ADC and TDC information feed the FPGA core, which builds up both measurements together for further readout by the control software.

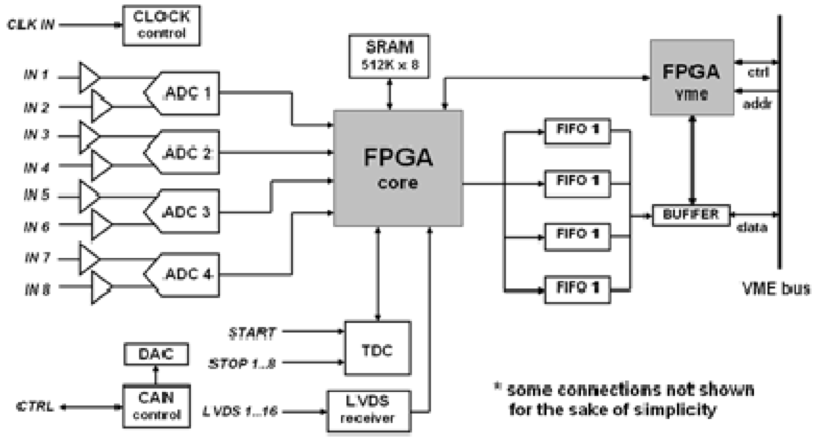

Fig. 3. Simplified block diagram of the 8 channel neutrino data acquisition module.

2.3 Data Simulation

We have used the GEANT4 [4] package to simulate the detector response to different geometries and PMT configurations. Fig. 4 shows the average number of registered photo-electrons from IBD events, generated by 2 MeV positrons and by gammas from neutron capture in the Gd [5]. The p.e. number is averaged over all PMTs. We see that the detector response for this typical event is quite clear and both products of IBD can be easily detected by summing up the signals of the PMTs.

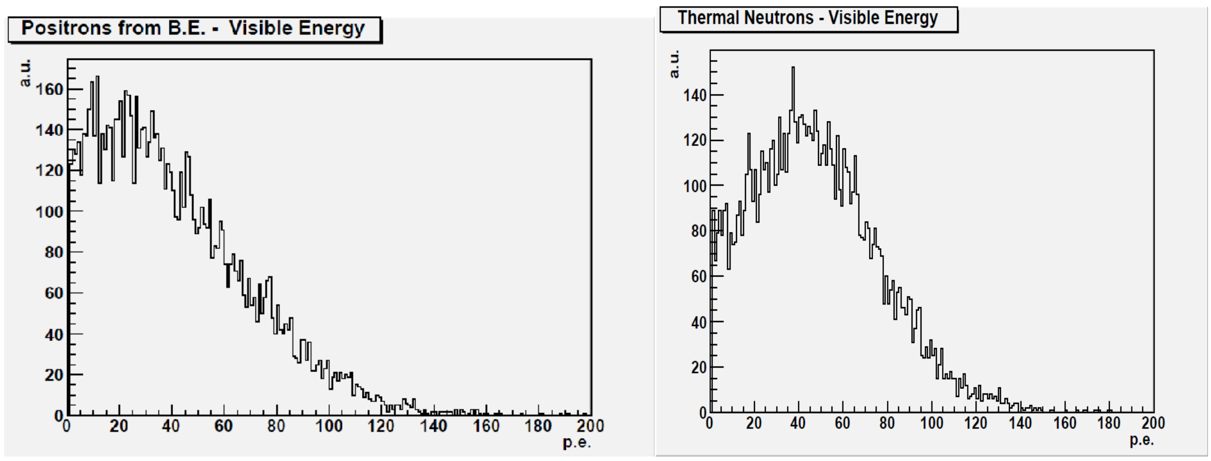

Fig. 4. Photo-electron distribution for positrons (left panel) and neutrons (right panel)

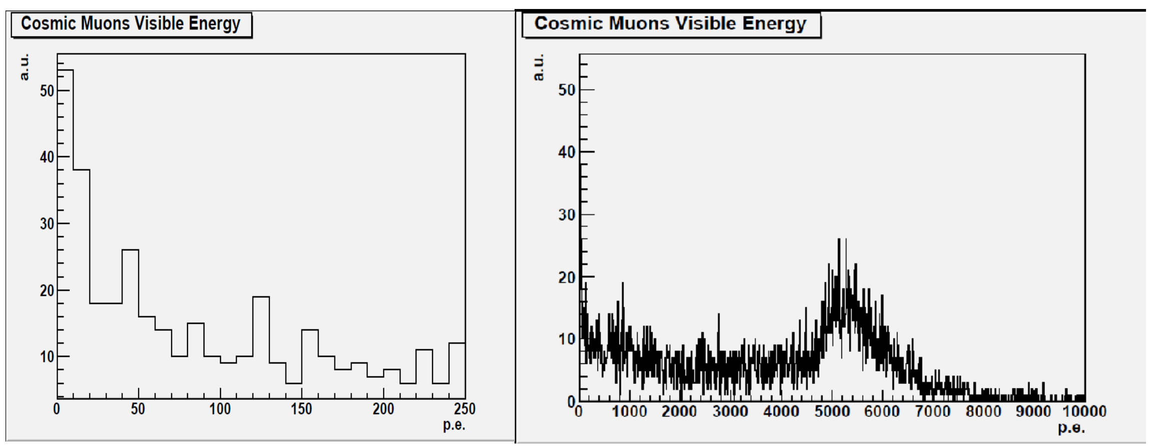

Fig. 5. Photo-electron distribution for muons entering the target volume:
a) close view of the 0-250 p.e. region; b) 0-10,000 p.e. region

We have also simulated the muon background entering the detector as shown in Fig. 5. As we can see in Fig. 5.b the mean number of p.e for muons is almost a factor hundred larger than IBD induced positrons and neutrons.

To estimate the energy resolution as a function of the antineutrino energy, we have simulated positrons uniformly inside the detector with different energies and the distributions of the total number of collected p.e. are analyzed [6]. We take as energy resolution the value of $\sigma(E)/E$ obtained in each distribution. The results are shown in Fig. 6. The average resolution for all energies is ~ 22%. Just for comparison we have simulated the detector in the same conditions but replacing the water with liquid scintillator. We can see that the energy resolution is about ~12%, half of that obtained with a Cherenkov detector as expected due the higher light yield of the liquid scintillator.

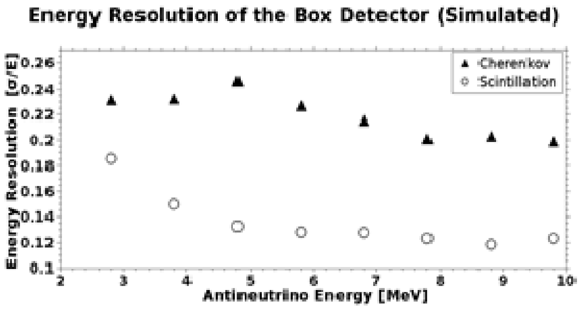

Fig. 6. Energy resolution as a function of the antineutrino energy, for water and liquid scintillator

2.4 Expected signal and background Rates

As we have mentioned before a target mass of 1 ton at a distance of 25 m will provide a neutrino interaction rate of ~ 5.3×10^3 events per day, equivalent to 0.06 Hz. Based on available cosmic ray experimental data at sea level [7] we have calculated the muon and neutron flux hitting the central detector which are the main sources of background that we will consider. We have obtained a muon rate of 350 Hz and a neutron rate of 4 Hz. To estimate the cosmic neutron rate we have taken into account an external passive shield of 30 cm of borated water. For these rates the signal to background ratio is about 1.64×10^{-4}. In order to reduce the background to acceptable levels we have to apply selection criteria to cut cosmic muons and neutrons from the data sample.

2.5 Data Simulation

To look for the best selection criteria that allow extracting the antineutrino signal we have simulated data events corresponding to one day of data taking [8]. From a given initial time t_o we have generated muons, cosmic neutrons and positrons according to Poisson distributions with mean value equal to the inverse of the frequency of occurrence of each particle. For IBD interactions the neutron signal was generated according to a Poisson distribution with initial time t_{0n} given by the positron prompt signal and having a mean value of 30 µs, characteristic time for the neutron thermalization and absorption by the Gd.

The criteria to define the selection cuts were based in the efficiency of muon identification by the outer veto and the characteristic time and energy deposit for each type of particle. As we can see in Fig. 4 and 5 positrons and neutrons deposit in most events less than 100 p.e. in the PMTs whereas muons deposit much more energy in 90% of the events. On the other hand most of the muons come from the top to the bottom of the detector and have a zenital distribution like $\cos^2\theta$. As the Cherenkov light cone axis develops in the muon momentum direction, most of the muon energy will be deposit in the bottom PMTs. Finally the time distribution of cosmic neutrons is not correlated with the time distribution of the positrons in opposition of what happens with the IBD neutron distribution. These will be our main selection criteria.

After ordering all particle signals with respect to t_0 we have applied the selection criteria discussed above to reject background: i) outer veto muon rejection efficiency of 98%; ii) total energy deposited in bottom PMTs > 100 p.e.; iii) ratio in the number of p.e. for top PMTs and bottom PMTs > 0.05; iv) time interval between two consecutive signals > 300 µs.

The selection cuts and their effect on each particle type are shown in Table. 1. As we can see the number of muons is drastically reduced but the number of cosmic neutrons is still one order of magnitude larger than the signal in the 0-300 μs window.

Table 1: simulated data for 1 day of data taking and data reduction by each selection criteria

	Muons	Cosmic Neutrons	Positrons*	Neutrons*	Total
Generated	29897690	341806	5252	5252	30250000
External Veto (98% Efficiency)	598383	341806	5252	5252	950693
Energy > 100 p.e.	30361	341806	5252	5252	382671
up/down ratio < 0.05	25208	339090	5215	5209	374722
Time window 0 – 300μs	4797	64468	5215	5209	79689
Time window 150 – 300 μs	2419	32137	285	282	35123
Time window 0 – 100μs	1718	23118	5035	5027	34898

As 96% of the IBD positrons and neutrons are in a 100 μs delayed coincidence window we will use the 150-300 μs time window between two consecutive signals to fit the muon and cosmic neutron background in this region. A linear background gives a very good fit and we have verified using the generated data that this fit can be extrapolated to describe the whole region 0-300 μs (see Fig. 7.a). To fit the signal in the 0-100 μs window we will use an exponential plus the linear function with fixed parameters just described (see Fig. 7.b). Once the parameters of the exponential are obtained the expected number of neutrinos is given by the integral of the exponential in the interval 0-100 μs.

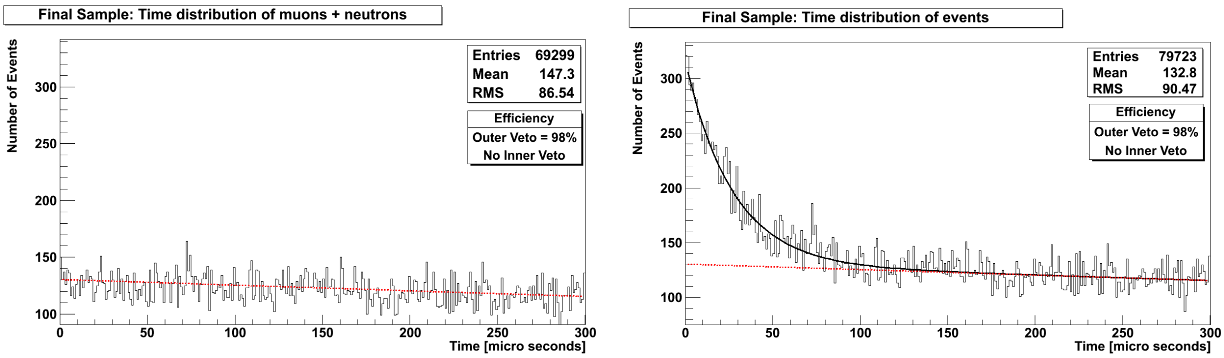

Fig. 7: a) muon + cosmic neutron background, linear fit; b) signal fit: exponential + linear background

Using this procedure we have estimated the number of antineutrinos corresponding to one day of data acquisition. In Table 2 we show the fit result for the number of antineutrino and background events compared with the generated number of signal and background events for two different efficiencies of the muon outer veto. As we see in the best case they agree within 3%.

Table 2: Generated and fitted number of events for two efficiencies of the muon outer veto.

External Veto	Neutrinos Events (100μs window)		Background Events
Efficiency	Fit Result	Simulated	(0-300μs)
95%	4824	5023	76857
98%	4873	5023	69677

To estimate the goodness of the fit we have estimated its precision using the expression

$$P = 100 \times \sqrt{\left(\Delta^2 / N^2{}_{fit}\right)}$$

where N_{fit} is the result of the integral of the exponential in the interval 0-100 μs obtained with the optimized parameters and Δ is the difference of the integrals considering the optimized parameters plus or minus the associated error divided by two. As shown in Fig. 8 we obtain a precision of 8% in the number of antineutrinos after one day of data taking.

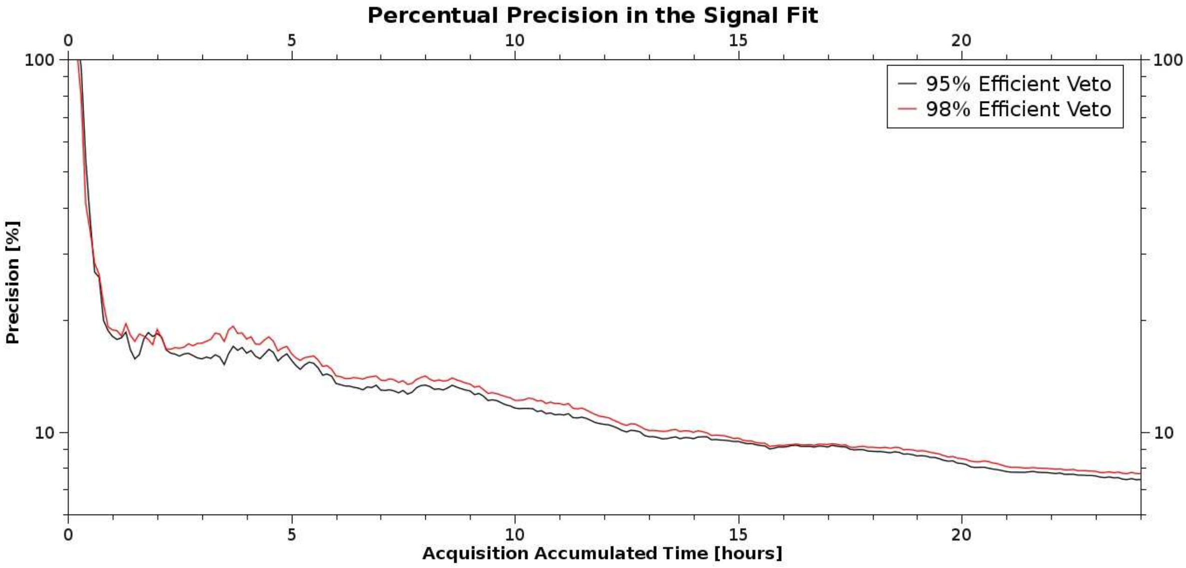

Fig. 8. Precision in the determination of the number of antineutrinos as a function of accumulated data (in hours) for one day of data taking.

3. Conclusions

The Angra project is finalizing its design phase. Simulation is running and guiding the final detector design. Safety restrictions on the use of liquid scintillator and the impossibility to dig a shaft near the reactor core led to a very challenging design: a water Cherenkov detector operating above ground. The main challenge will be to overcome the very large background generated by cosmic rays.

A laboratory is already deployed in a commercial container next to the Angra II reactor containment building where measurements of the local muon background have been performed. An internet link to the Centro Brasileiro de Pesquisas Fisicas in Rio de Janeiro has been established allowing remote data acquisition and monitoring of the experiment.

Prototypes of the 8 channel VME based electronics for data acquisition have been tested and the production of the modules is underway. All the PMTs and other major components have been purchased and the detector construction is scheduled to start in July 2011. Data taking is expected to start at the beginning of 2012.

We have presented in this paper our data analysis strategy to overcome the main sources of background for detectors located above ground: muons and fast neutrons produced in hadron showers induced by cosmic rays. We have simulated one day of data taking generating positrons and neutrons from antineutrino interactions and muons and cosmic neutrons. We have shown that criteria based on the efficiency of muon identification by an outer veto and the characteristic time and energy deposit for each type of particle can provide selection criteria to reduce drastically the background, allowing a determination of the number of antineutrino interactions with a precision of the order of 8%.

With the Angra detector we expect to observe the on–off status of the reactor, the power level and the fuel burn-up effect. We hope that these developments will allow incorporating, in the long term, the antineutrino detection technology into safeguards tools to be used by the International Atomic Energy Agency.

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