

Cosmic muon background and reactor neutrino detectors: the Angra experiment

E Casimiro^{1,2} and J C Anjos²

¹ CINVESTAV-IPN, Av. IPN 2508, Col. Zacatenco, AP 14740, Mexico DF 07000, Mexico

² CBPF, Rua Dr. Xavier Sigaud, 150, Urca, Rio de Janeiro, Brazil, CEP 22290-180

E-mail: elinares@fis.cinvestav.mx

Abstract. We discuss on the importance of appropriately taking into account the cosmic background in the design of reactor neutrino detectors. In particular, as a practical study case, we describe the Angra Project, a new reactor neutrino oscillation experiment proposed to be built in the coming years at the Brazilian nuclear power complex, located near the Angra dos Reis city. The main goal of the experiment is to measure with high precision θ_{13} , the last unknown of the three neutrino mixing angles. The experiment will in addition explore the possibility of using neutrino detectors for purposes of safeguards and non-proliferation of nuclear weapons.

1. Introduction

In this contribution we discuss the importance of appropriately taking into account the cosmic background in the design of reactor neutrino detectors. In particular, as a practical study case, we describe the main design features of the recently proposed Angra neutrino experiment.

The Angra Project [1] aims to measure antineutrino disappearance. It will use as the source of neutrinos the reactors from the Brazilian nuclear power complex, located about 150 km south from Rio de Janeiro, near the Angra dos Reis city.

The experimental approach consists in measuring the neutrino flux and energy spectra at two different distances from the reactor core:

- *Near* the reactor core, 300 m away from it, with a 50-ton mass Near Detector (ND).
- *Far* from the reactor core, at a distance of ≈ 1.5 km from it, with a 500-ton mass Far Detector (FD).

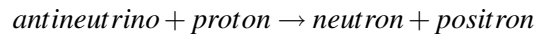
In an early phase of the experiment, the Angra collaboration will build a small (about 1-ton mass detector), to be placed at a distance of about 70 m from one of the reactor cores (Angra II). This Very Near Detector (VND) will constitute a first prototype to test concepts and elements for the subsequent implementation of the ND and the FD and will as well constitute a new technology tool effort towards the development of applications in the framework of the international program promoted by the IAEA to develop tools for safeguards and non-proliferation of nuclear weapons.

2. Reactor Neutrino Experiments

Neutrinos—and antineutrinos—interact with matter so faintly that it is extremely hard to detect them. This difficulty, the low-interaction probability, can be palliated by the fact that nuclear reactors produce extraordinarily large fluxes of antineutrinos ($\sim 10^{20}$ per second), thus making plausible the practical

detection of neutrinos by means of carefully designed massive detectors located close to the reactor core. The first neutrinos ever detected (Reines and Cowan team, mid 1950s) made use of this approach.

Reactor neutrino detectors have typically exploited the inverse beta decay process



to identify antineutrinos through their interaction with the protons of the detector target. The detector usually consists of a transparent scintillator material (with some other chemicals added). The signature of a neutrino candidate is then indicated by two optical signals (that are converted into electrical signals by the use of properly located photomultiplier tubes, PMTs). The first signal comes from the rapid positron annihilation. The second signal, coming from the capture of the neutron, appears about 30 microseconds later. Each of these two signals has a characteristic energy.

Although the detection principle is simple there are many practical difficulties involved. Particularly important is the fact that the clean identification of the neutrinos is hindered by cosmogenic background; the topic will be covered in more detail later in the document.

3. Nuclear Safeguards

Several studies have pointed out the feasibility of using the antineutrino emission from nuclear reactors to monitor the reactor activity. Neutrino detector experiments with this goal were performed since the 80s at the Rovno nuclear power plant (Ukraine) [2]. A more recent detector prototype with the same goal [3] began taking data in 2003 at the San Onofre Nuclear Generating Station (San Clemente, California) and has obtained encouraging results.

The flux of antineutrinos emitted from the reactor core is closely related to the thermal power of the reactor. By measuring with high precision the antineutrino energy spectrum it is in principle possible to determine not only the thermal power of the reactor, but also, up to some degree, its fuel isotopic contents. The fractions of fissile material in the reactor core change over time along the fuel cycle. The contents of fissile material in the reactor at a given time could be determined by the measurement of the neutrino flux over time—some fissile isotopes produce more neutrinos than others—or by measuring changes in the energy spectrum of the emitted antineutrinos—the energy spectra for antineutrinos from different isotopes are different—. The measurement over time of the antineutrino emission rate and of the antineutrino energy spectra can thus indicate the fractions of fissile elements present in the reactor fuel. It may thus be feasible to achieve a measurement of the relative amounts of uranium and plutonium in the fuel.

Again, we emphasize that since the monitoring of the reactor with this method relies on neutrino detection, the performance of the monitoring tool is strongly dependent on the understanding and attentive control of the cosmogenic background.

4. Cosmic Background in Neutrino Detectors

One of the severe limitations in detecting neutrino signals from reactors is the presence of the interfering cosmic ray background. While at ground level many components of cosmic radiation are copiously present, usually it is considered that only the very penetrating muons—and of course the faintly interacting neutrinos—are still importantly present down underground, the other components having been “absorbed” by the soil material even at depths as shallow as a few meters of rock under the ground level.

In order to reduce as much as possible the cosmic background, neutrino detectors are usually located underground, with a considerable overburden. However there are practical limitations that do restrain from locating the detector at large depths, e.g., digging very deep shafts near reactor buildings might not be permitted for safety reasons. Furthermore, in some cases the detectors are purposely located at shallow depths in order to accomplish some desirable experimental features. It is usually crucial for instance to keep the detector as close as possible to the reactor core, generally located itself at ground

level. The Angra Very Near Detector for instance, is envisaged to be located at a depth underground of about 20 to 50 meters of water equivalent (mwe) overburden.

Knowledge of the underground cosmic muon flux is important for neutrino experiments (e.g., reactor experiments looking to measure $\sin^2 2\theta_{13}$) for several reasons. Spallation neutrons produced by cosmic muons in the material surrounding the detector (e.g., in the rock) and in the detector material itself (e.g., in the liquid scintillator) constitute a major problem. These cosmic-muon induced neutrons can result in signals having the same time and space characteristics as those associated with reactor neutrinos, i.e., cosmogenic neutrons can fake neutrino signals.

In neutrino detectors often cosmic muons are identified by some sort of muon detector (e.g., an array of plastic scintillators or liquid scintillator material) surrounding or covering the main body of the detector. A veto (on-line or off-line) of a certain duration can then be applied to the whole detector during a certain time upon the passage of a cosmic muon through the veto system. However since cosmogenic neutrons live in average long times before being captured, the use of a simple veto during a time window to try to get rid of them, would result in unacceptable large deadtimes for the detector. Furthermore, muons passing by in the vicinity of the detector but not passing through the muon veto system—necessarily having limited coverage area due to practical reasons—, can as well produce spallation neutrons in the surrounding material that can finally reach the detector without any correlated veto signal. Spallation neutrons thus constitute a major problem, difficult to deal with. Covering hermetically the neutrino detector with scintillator paddles collocated following a not conscientious design is for example not necessarily a sufficient means to account for the cosmogenic background. A more careful approach would require using a large-area scintillator umbrella combined with some lateral and underlying detectors.

In order to better illustrate the importance of the muon cosmic background for reactor neutrino detectors we should mention that for most practical reactor neutrino detectors the cosmic muon flux coming into the detector is several orders of magnitude larger than the corresponding neutrino flux. A practical high-performance detector located close to the reactor core, at a few tens of meters from it, shall register only a few hundreds of neutrino events per day. In other hand, it will have to cope with a rate of muons hitting the detector—or passing in the immediate vicinity of the detector volume—of several hundreds of events per second, even if it is equipped with a reasonable overburden or shielding. The number of cosmic muons arriving to the detector exceeds largely the corresponding number of neutrinos.

5. The Angra Experiment

5.1. The Nuclear Reactor Complex

The Brazilian nuclear power facility is located about 150 km south from Rio de Janeiro, near the Angra dos Reis city. Currently the Angra nuclear reactor complex has two operational reactors: Angra I and Angra II. The approval of the construction of a third reactor, Angra III, essentially similar to Angra II, is currently being reviewed—the preparation of the foundations of the reactor building have already begun. The nominal output thermal power of the reactors are: Angra I – 2 GW, Angra II – 4 GW. The state-owned company Eletronuclear is responsible for the management and operation of the plant.

5.2. The Angra Site

The topology of the surrounding mountainous granite terrain is an important advantage of the site: at about 1.5 km from the Angra II reactor we find (see Fig. 1) the ≈ 700 m high peak of the mountain called *Morro do Frade* providing with an overburden of about 2000 mwe at a suitable distance for neutrino oscillation measurements. As it was mentioned before, a large overburden results in an important reduction in cosmogenic noise signals. In Fig. 2 we present a plot of the expected vertical muon flux as a function of the overburden. As can be seen in the figure, the Angra FD site has an overburden comparable to other dedicated deep underground facilities; thus, a substantial reduction of the cosmic induced background can be achieved. By combining the use of a carefully designed large detector and this

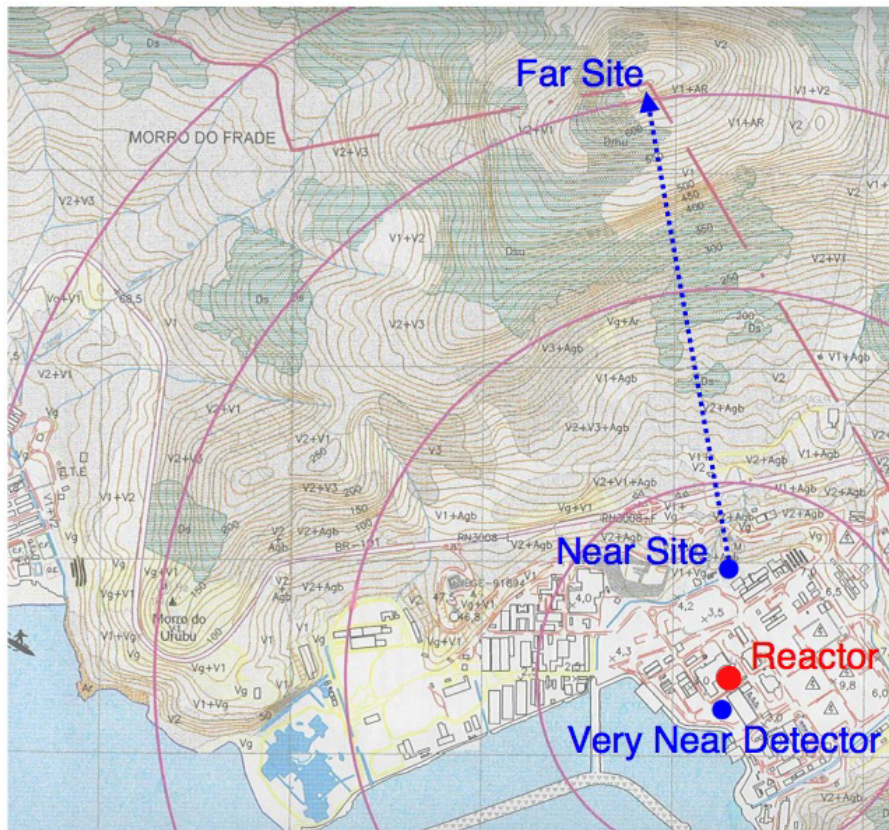


Figure 1. Map of the Angra neutrino detector region.

massive overburden the Angra experiment can reach an unprecedented sensitivity in the determination of θ_{13} .

5.3. The Detectors

The Angra neutrino oscillation experiment will consist of two neutrino detectors to be collocated in the Near-Far configuration described above. In a first development phase, we will build a small prototype detector. The VND, ND and FD will all have the same basic design. They however will be of different size: they will be scaled according to their distance to the reactors in order to measure each of them comparable neutrino detection rates.

5.3.1. The antineutrino detector The antineutrino detector (Fig. 3) comprehends three concentric volume regions. Each of these regions has a specific purpose.

- *The Target*, the innermost volume, filled with liquid scintillator slightly doped with gadolinium (in a concentration of $\approx 0.1\%$) in order to achieve high efficiencies to identify inverse beta decay events (because of the gadolinium high cross-section for neutron capture).
- *The Gamma Catcher*, the intermediate volume, filled with standard liquid scintillator in order to increase the detection volume (relative to the target volume) for gammas from neutron capture.
- *The Buffer*, the outermost volume, filled with non-scintillating mineral oil, mainly intended to reduce residual radioactivity background from the material surrounding the detector.

Several dozens of 8-inch photomultiplier tubes are installed in the outer wall of the buffer (looking inwards) resulting in a surface coverage of about 12%. The organic liquid scintillator is a solvent mixture

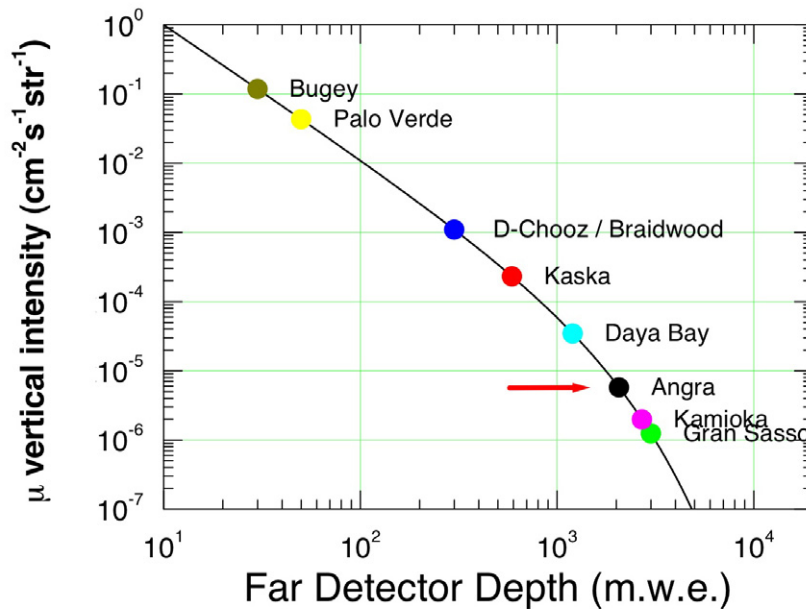


Figure 2. Muon vertical intensity as a function of depth for several underground research facilities.

with a basic component like C_nH_{2n+2} and additional chemical components to enhance scintillation and mold the optical properties of the liquid. The protons of the compound provide the targets for the inverse beta decay antineutrino interaction. The addition of gadolinium to the scintillator of the target volume results in an important increase of the neutron capture cross section. The neutrino signature is the detection in time-delayed coincidence of the positron and the neutron. The positron annihilation produces the *prompt* signal; a subsequent detection of gammas from the neutron capture provides the *delayed* signal. Each of the two signals has a characteristic energy.

5.4. The Muon Veto

Each of the antineutrino detector uses a crucial associated system: a muon veto. The muon veto in each case is composed of a set of muon scintillator paddles in a large-area umbrella geometry (the actual large size is not properly illustrated in the figure), located above the detector. Two planes (XY) of paddles will be used in order to better identify and localize the passage of muons and allow the implementation of coincidence triggers. Additional planes of scintillator paddles located below the detector will also be used in order to enable muon tracking capabilities for muons crossing the detector or passing close by. Vertical paddles will further allow to identify large-angle trajectory muons and will in general enhance the muon characterization capabilities of the experiment. All paddles will have phototubes attached at both ends. After a veto signal generated in the the muon system, the whole detector will be vetoed (on-line or off-line) during a certain time window.

5.5. The Very Near Detector

We are currently developing the very near detector. It will serve as a prototype to test the different detector elements and also as a survey tool for performance studies. The VND will additionally work as a non-intrusive nuclear reactor monitor within the framework of the international effort promoted by the IAEA to develop tools for safeguards and non-proliferation of nuclear weapons.

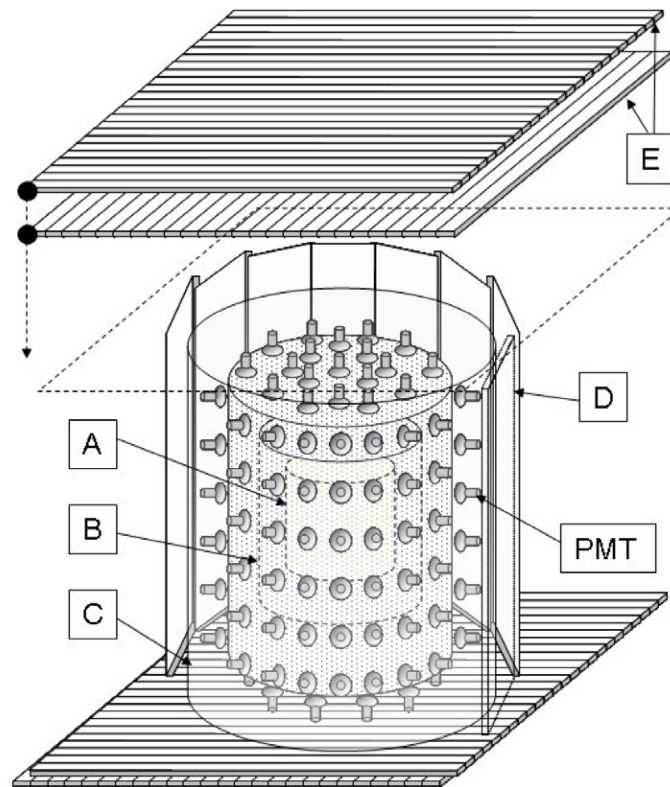


Figure 3. Conceptual design of the Angra neutrino detector. A: Target; B: Gamma Catcher; C: Buffer; D,E: Muon Veto.

6. Summary

We have shown the importance of appropriately taking into account the cosmic background in order to be able to construct and operate successfully neutrino detectors for nuclear reactors.

We have presented the basic ideas behind the experimental conception of the Angra neutrino experiment. In a first stage, we are developing a small prototype detector close to the reactor core. It will serve as a prototype to test the different detector elements and as a survey tool for performance studies. It will also be used to monitor the reactor activity, and will provide with a tool for verification of safeguards and non-proliferation of nuclear weapons.

We are currently fine-tuning the detector design parameters. We are working out the design and giving the first steps towards the implementation of the front-end electronics and of the data acquisition systems for the detectors. For the time being the design and implementation tests are taking place in the laboratories of the involved institutions. We intend to start experimental activities in the Angra site by mid 2007, The Very Near Detector is planned to begin operating in 2009. The complete Angra setup should be ready by 2014.

Acknowledgments

This work was supported in part by the CLAF, the CNPQ-Brazil and the CONACYT-Mexico.

References

- [1] Anjos J C *et al.* 2006 *Nucl. Phys. Proc. Suppl.* **155** 231
- [2] Klimov Y V *et al.* 1994 *Atomic Energy* **76** 2
- [3] Bernstein A *et al.* 2001 *Nuclear reactor safeguards and monitoring with anti-neutrino detectors* (Preprint nucl-ex/0108001)