Neutrinos for Peace

2015 J. Phys.: Conf. Ser. 593 012004

(http://iopscience.iop.org/1742-6596/593/1/012004)

Neutrinos for Peace

M Cribier
CEA-Saclay • DSM/Irfu/SPP
F- 91191 Gif-sur-Yvette Cedex

E-mail: mcribier@cea.fr

Abstract. The fundamental knowledge on neutrinos acquired in the recent years open the possibility of applied neutrino physics. Among it the automatic and non intrusive monitoring of nuclear reactor by its antineutrino signal could be very valuable to IAEA in charge of the control of nuclear power plants. Several efforts worldwide have already started.

1. Introduction

The International Atomic Energy Agency (IAEA) is the United Nations agency in charge of the development of peaceful use of atomic energy. In particular IAEA is the verification authority of the Treaty on the Nonproliferation of Nuclear Weapons (NPT). To do that job inspections of nuclear installations and related facilities under safeguards agreements are made in more than 140 states. IAEA uses many different tools for these verifications, like neutron monitor, gamma spectroscopy, video camera, but also book keeping of the fuel element composition before and after their use in the nuclear power station. In particular it verify that weapon-origin and other fissile materials that Russia and USA have released from their defence programmes are used for civil application.

Looking for innovative methods, the IAEA ask members states to make a feasibility study to determine whether antineutrino detection methods might provide new practical safeguards tools for selected applications. If this method proves to be useful, IAEA has the power to decide that any new nuclear power plants built has to include an antineutrino monitor. Actually, not only powerful reactors are of concern, but also research reactors where loading and unloading of nuclear fuel are much more easy and frequent. Except an experimental device, IAEA today has no tool to monitor the power of reactors under control.

To organize this work, there have been three workshops on safeguard application of neutrinos held by IAEA since 2003 [IAEA]. In these workshops, IAEA staffs and neutrino physicists from all over the world exchanged information on safeguard needs and possibilities of reactor neutrino monitoring and both parties have agreed to proceed to study this option. The neutrino physicists hold Applied AntiNeutrino Physics Workshop annually since 2004 [3] with attendance from IAEA.

2. Physic basis

In a new reactor with normal water cooling the initial fuel consist of enriched uranium rods, with an ^{235}U content typically at 3.5%, the rest is ^{238}U. As soon as the reactor is operating, reactions of neutron capture on ^{238}U produce ^{239}Pu (and ^{241}Pu), which then contribute also to the energy production. Nevertheless the net balance in plutonium is positive and a standard pressurized water power reactor produces around 200 kg of plutonium per year.

An atomic weapon could be built either with very enriched ^{235}U or with very pure ^{239}Pu. Typical critical masses are a few kilograms.

Every fission of a fissile isotope produce two fissions fragments of unequal masses. The distribution of the lightest fragment is centred around A = 94 for fission of ^{235}U, and centred around A = 102 in the case of ^{239}Pu. All these nuclei, too rich in neutrons, are extremely unstable and thus beta decay toward stable nuclei with an average emission of 6 ß decays and thus with 6 antineutrinos. In these processes several hundreds of unstable nuclei, with their excited states are involved, which makes very difficult to understand details of the physics; moreover, the most energetic antineutrinos, which are detected more easily by the neutrinos detectors, are produced in the very first decays, involving nuclei with typical lifetime much smaller than a second.

	^{235}U	^{239}Pu
released energy per fission	201.7 MeV	210.0 MeV
Mean energy of ν	2.94 MeV	2.84 MeV
ν per fission > 1.8 MeV	1.92	1.45
average inter. cross section	≈ 3.2 10^{-43} cm^2	≈ 2.76 10^{-43} cm^2

Table. Main characteristics of antineutrinos originating from ^{235}U and ^{239}Pu fission

Nevertheless based on predicted and observed ß spectra, the number of antineutrinos per fission from ^{239}Pu is known to be less than the number from ^{235}U, and the energy released bigger by 5%. Hence an hypothetical reactor able to use only ^{235}U would induce in a detector an antineutrino signal 60% higher than the same reactor producing the same amount of energy but burning only ^{239}Pu (see table). This sizeable difference offer a handle to monitor changes in the relative amounts of ^{235}U and ^{239}Pu in the core. Merged with the high penetration power of antineutrinos, this provide a new mean to make remote, nonintrusive measurements of plutonium content in reactors offering a way to predict the amount of plutonium produced in the installation undeer surveillance [1].

In most of the presently considered detectors, antineutrinos are detected via the inverse beta decay process on quasi-free protons in hydrogenous scintillator: $\overline{\nu}_e + p \rightarrow e^+ + n$ □ν_e, with a threshold at 1.8 MeV. The positron and the neutron are detected in a delayed coincidence, allowing strong rejection of the much more frequent singles backgrounds due to natural radioactivity.

Because the antineutrino signal from the reactor decreases as the square of the distance from the reactor to the detector a precise "remote" measurement is really only practical at distances of a few tens of meters if one is constrained to "small" detectors of the order of few cubic meter in size.

3. Pioneers in Kurchatov

The potentiality to address certain safeguards applications was recognized long time ago by Mikaelian et al. [2]. The correlation of the antineutrino signal with the thermal power and the burn-up was demonstrated by the Bugey [3] and Rovno experiments [4]. What makes this old idea possible today is our present understanding of the oscillation mechanism which guarantee that the signal recorded by a neutrino detector at less than 200 meters from a reactor is not significantly affected, or could be corrected for. In this respect the results of KamLAND detector [5] as a global monitor of remote ≈ 180 km) power plants is impressive.

Following this tradition the DANSS group [6] build a new detector to be installed at 10-20 m from the Kalinin nuclear power plant.

4. Efforts in the USA

The experimental program for development of nonproliferation detectors in the United States is led by Lawrence Livermore National Laboratory and Sandia National Laboratories. The LLNL/SNL work has consisted of installing and operating a prototype detector at the 3.46 GWth San Onofre Nuclear Generating Station (SONGS) in Southern California. The detector [7] was operated at SONGS at a distance of 24.5 meters from the core in the tendon gallery and with an overburden of about 25 m.w.e.

Journal of Physics: Conference Series **593** (2015) 012004 doi:10.1088/1742-6596/593/1/012004

The shielding consists of a muon veto system for rejecting cosmic ray backgrounds, a water/polyethylene shield to reject neutron and gamma backgrounds. The central detector, which registers antineutrino interactions, has a one cubic meter active liquid scintillator doped with gadolinium (0.64 ± 0.06 ton), seen by eight 9” PMTs. The overall footprint including shielding is 2.5 meter × 3 meter.

In this condition the rate predicted at the beginning of the reactor fuel cycle is approximately 3800 ± 440 antineutrino interactions per day for a perfectly efficient detector. The overall efficiency to detect antineutrino interaction via positron neutron delayed coincidence is 10.7% with a signal to background close to 4. The number of antineutrino events observed, 459 ± 16/day is in good agreement with the expected rate deduced from simulation.

Changes in reactor power can quickly (within a few hours) be detected by tracking the antineutrino rate. The plot of daily rate versus time (Figure 1) also shows a two sigma deviation of the antineutrino rate from a constant value over a six month period, with the linear reduction in total rate consistent with a prediction that includes a fuel burn up estimate. Between the two cycles operation of refueling take place replacing xxx fuels rods containing ≈ xxx kg of plutonium by the same number of rods without plutonium. The gap in the events rate demonstrate the present sensitivity of this antineutrino monitor : it is estimated that removal 70 kg of ^{239}Pu can be detected with 95% C.L.. Already these results, although modest for neutrino specialists, are convincing enough for external viewers which correlate usually a neutrino detector with a huge apparatus.

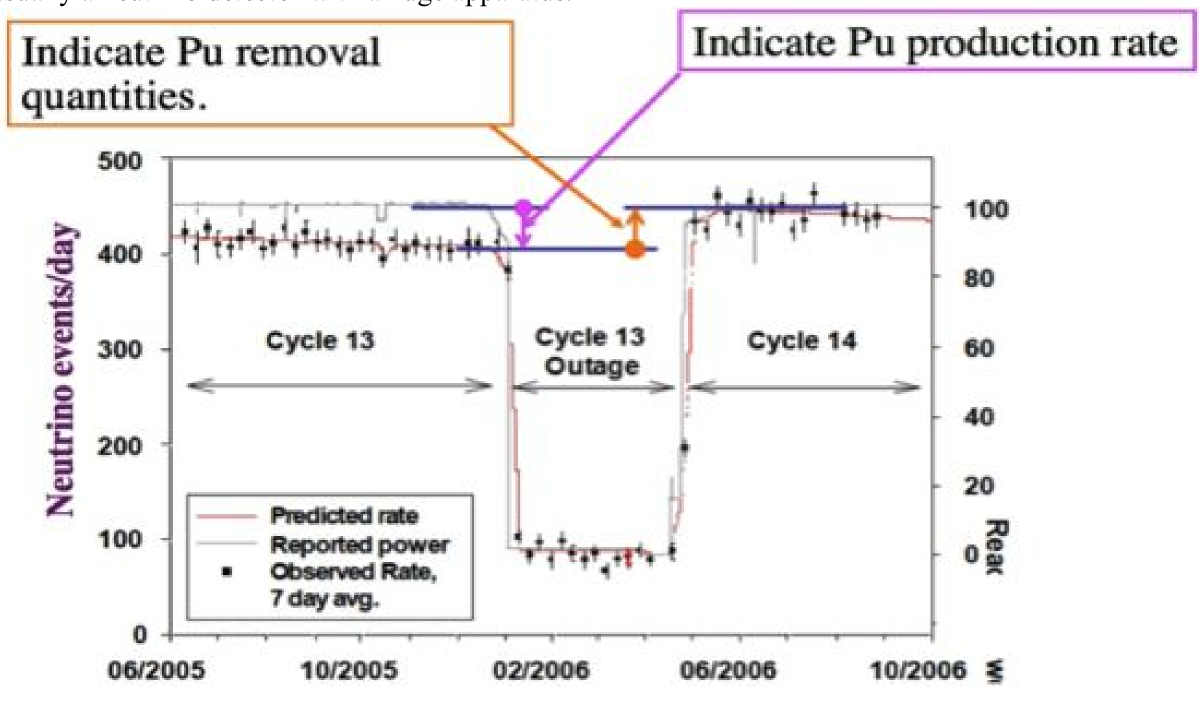

Figure 1. Effect of Refueling showing the sensitivity to a removal of 70 kg of 239Pu.

5. Efforts in France

The Double Chooz collaboration, an experiment [8] mainly devoted to study the fundamental properties of neutrinos, is also in a good position to evaluate the interest of using antineutrino detection to remotely monitor nuclear power station. Indeed, without any extra experimental effort, the near detector of the Double Chooz experiment will provide the most important data set of antineutrino detected ($5x10^5$ ν per year). The precise energy spectrum recorded at a given time will be correlated to the fuel composition and to the thermal power provided by EDF; it is expected that individual component due to fissile element (^{235}U, ^{239}Pu) could be extracted with some modest precision and serve as a benchmark of this techniques.

Journal of Physics: Conference Series **593** (2015) 012004 doi:10.1088/1742-6596/593/1/012004

5.1. Toward a better understanding of the antineutrino spectrum

The IAEA recommends the study of specific safeguards scenarios. Among its concerns are the confirmation of the absence of unrecorded production of fissile material in declared reactors and the monitoring of the burn-up of a reactor core. The time required to manufacture an actual weapon estimated by the IAEA (conversion time), for plutonium in partially irradiated or spent fuel, lies between 1 and 3 months. The significant quantity of plutonium is 8 kg, to be compared with the 3 tons of ^{235}U contained in a Pressurized Water Reactor (PWR) of power 900MWe enriched to 3%. The small magnitude of the expected signal requires a careful feasibility study.

The proliferation scenarios of interest involve different kinds of nuclear power plants such as light water or heavy water reactors (PWR, BWR, Candu...), it has to include isotope production reactors of a few tens of MWth, and future reactors (e.g., PBMRs, Gen IV reactors, accelerator-driven sub-critical assemblies for transmutation, molten salt reactors). To perform these studies, core simulations with dedicated Monte-Carlo codes are being developed in France. The particle transport code MCNPX coupled with an evolution code solving the Bateman equations for the fission products are combined within a package called MURE (MCNP Utility for Reactor Evolution) [9]. It computes accurately the amount of all β- emitters produced during the operation of a nuclear power plant.

To fulfil the goal of nonproliferation, additional laboratory tests and theoretical calculations should also be performed to more precisely estimate the underlying neutrino spectra of plutonium and uranium fission products, especially at high energies. As concluded by P. Huber and Th. Schwetz [10] to achieve this goal a reduction of the present errors on the antineutrino fluxes of about a factor of three is necessary. This is the basis to the important effort to better understand the antineutrino spectrum. More details can be found in S. Cormon thesis [11].

A re-evaluation of the antineutrino spectrum from fission has been performed using available experimental data on the energy and spin and parity of all known nuclear levels involved [12]. The shape and error of individual β-branches has revealed some systematic biases in the previously published data. Indeed starting from very precise electron spectrum measured at ILL [13] resulting from the fission of the above nuclei you have to predict the spectrum of antineutrino ; if this operation called conversion is trivial for allowed ß transitions it is more and more difficult when the ß spectrum result from forbiden transitions.

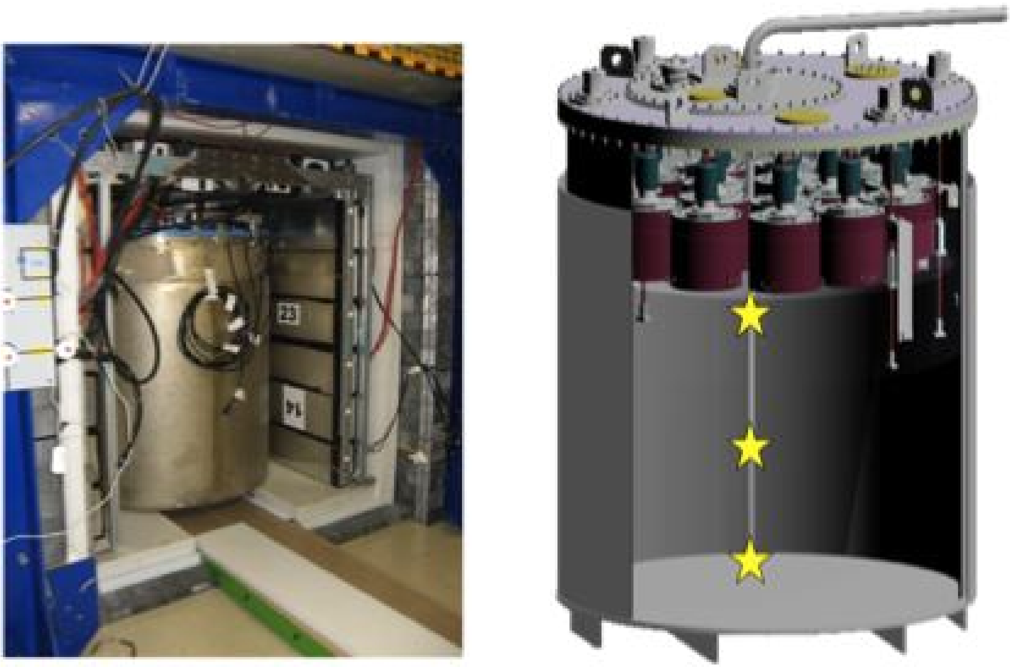

Figure 2. The Nucifer detector

5.2. Nucifer.
The Nucifer [14] detector target is a stainless steel vessel of 1.8 m in height, and 1.2 m in diameter filled with about 0.85 m^3 of Gd-doped liquid scintillator (EJ335 from Eljen technology). The internal surface of the vessel is coated with Teflon to ensure the compatibility with the liquid scintillator and to increase the light reflections. All mechanical parts, in particular welding materials, are low radioactive materials. The photodetection system is based on 16 large (8 inches in diameter, R5912) photomultipliers (PMTs) from Hamamatsu, providing a large dynamic of light detection from the single photoelectron to few hundreds of photoelectrons and ensuring an efficient light collection. PMTs are coupled to a 250 mm thick acrylic vessel placed at the top of the target vessel. This so-called acrylic buffer aims at ensuring the uniformity of the response in the whole target volume while reducing the light generated by the intrinsic PMT radioactivity in the scintillator. 80 liters of mineral oil are used to ensure the optical coupling between the PMTs and the acrylic.

The Nucifer experiment take data at the Osiris research reactor (70 MW_{th}) at only 7 meters from the core. This detector, funded by the CEA-DAM, is a simplified version of a neutrino detector built as a prototype for a future neutrino monitor. In this respect compromise has been made to respect certain criteria of simplificity and overal size to try to match requirements of IAEA.

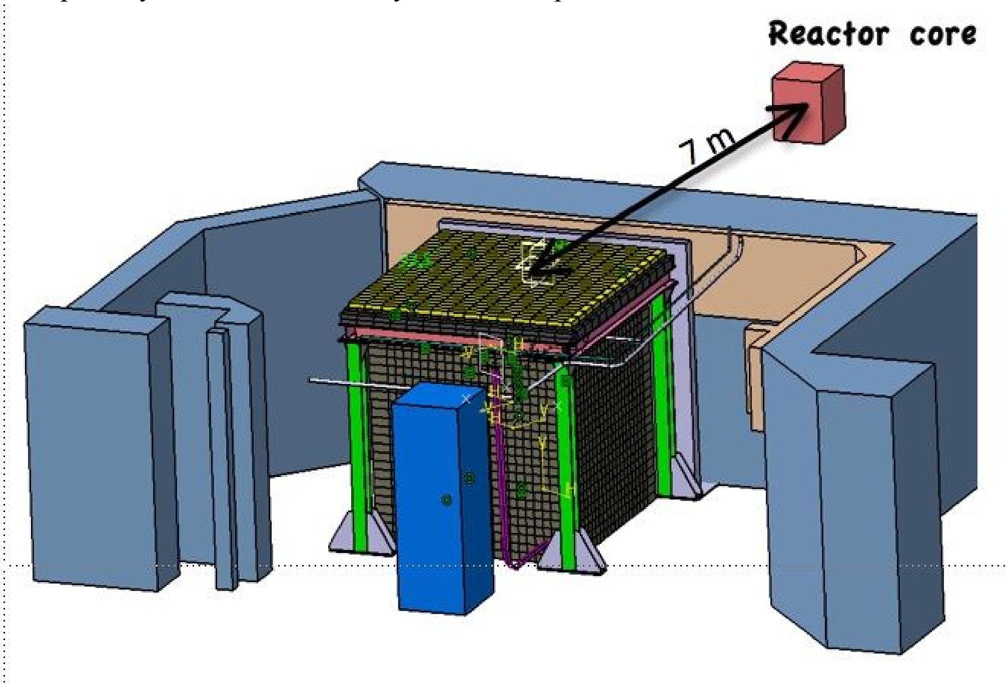

Figure 3. The Nucifer implementation at the Osiris reactor at Saclay

6. Effort in Japan

6.1. KASKA [15]
A Gd-loaded liquid scintillator detector was developed as a prototype detector for the reactor θ13 project in Japan called KASKA (*KAShiwazaki-KAriwa* nuclear power station). The group tried to detect neutrinos from JOYO fast research reactor with 140 MWth power at above ground 24 m from the reactor core. The KASKA prototype detector is now being remodeled by making use of stable liquid scintillator, double layered structure and pulse shape neutron/gamma background separation capabilities

6.2. PANDA
PANDA (Plastic Anti-Neutrino Detector Array) lead by Tokyo University [16] uses segmented plastic scintillator modules with Gd-containing sheets in between. The size of one unit of plastic scintillator

quadratic prism is 10 cm x10 cm x 100 cm (10 kg) viewed by two photo multipliers from both side. It is noncombustible above ground mobile detector installed on a van. 360 kg (6 °—6 arrays) prototype detector was deployed by the Ohi reactor unit-2 (3.4 GWth) for two months in 2011- 2012. The distance from the reactor core was 36 m. The group marginally observed the reactor ON/OFF difference and demonstrated satisfactory unmanned field operation

7. Distant monitoring

Neutrinos travels long distance through dense materials without being stopped. Large liquid scintillators detectors already in operation like KamLAND or Borexino has demonstrated their abilities to detect signal from nuclear reactors at several hundred kilometers. Such antineutrino detectors forbids to totally hide some nuclear activities involving fission like a clandestine nuclear power or nuclear test. Moreover, in the case of a test, the unique signature given by the antineutrino interaction, in coincidence with other methods like seismic waves, transform an hint into a proof.

Based on this principal several groups around the world propose network of huge detectors able to detect, locate and measure the power of nuclear reactors and of bombs test. In the mean time a more modest neutrino detector used in coincidence with the standard seismic network could sign unambiguously the real nature of a kton test.

This aspect of the use of antineutrinos is the subject of a dedicated study treating in a realistic manner the real backgrounds in these large detectors [17]. In this approach HanoHano is a good example of such detector [18] and the Watchman program is launched in the US.

8. Neutrinos for Peace

All the applications of our knowledge of neutrinos seems surprising for physicists which, for many years, consider this particle as the most elusive one. It is remarquable that so quickly a very fundamental research could turn into applications: it is even more enjoyable that the first applications envisaged for this unusual particle is the control of arm races and not a new weapon as it happens so often in the past. For all these reasons, I gladly proposed at the conference Neutrino 2008 to name these worldwide efforts: *Neutrinos for Peace*.

References

[1] Bernstein A., et. al., 2002 *J. Appl. Phys.* **91** 4672
[2] Mikaelian L.A.,2007 *Proc. Int. Conference Neutrino-77*, v. 2, p. 383-387
[3] Declais Y.et al., 1995 *Nucl. Phys. B***434** 503
[4] Klimov Yu.V., et. al., 1994 *Atomic Energy* **76** 123
[5] Eguchi K.et al., KamLAND Collab., 2003, *Phys. Rev. Lett.* **90** 021802
[6] Alekseev I.t et al., 2013 DANSSino: a pilot version of the DANSS neutrino detector (*Preprint* physics-Ins.det./1305.3350)
[7] Bowden N.S.et al., 2007 *Nucl.Instrum.Meth. A***572** 985
[8] Ardellier F.et al.2006 Double Chooz: A search for the neutrino mixing angle θ_{13} (*Preprint,* hep ex/0606025)
[9] Mal'plan O. et al. 2005. *In Proceedings of the ENC* (CD-Rom) p1-7.
[10] Huber P., Schwetz Th., 2004, *Phys.Rev. D***70** 053011
[11] Cormon S.et al., *PhD Thesis* at Nantes, in french
[12] Mueller Th.A.et al.,2011 *Phys. Rev. C***83** 054615
[13] Schreckenbach K.et al., 1985, *Phys. Lett. B***160** 325
[14] Porta A.et al., 2010, *IEEE Transactions on Nuclear Science* **57**, 2732
[15] Furuta H., Fukuda Y., Hara T., Haruna T., et al., 2012, *Nucl. Inst.Meth. A* **662** 90.
[16] Kuroda Y., Oguri S., Kato Y., Nakata R. et al., 2012 *Nucl. Inst. Meth. A* **690** 41
[17] Lasserre T.et al.,2010 SNIF: A Futuristic Neutrino Probe for Undeclared Nuclear Fission Reactors, (*Preprint*/1011.3850)
[18] Learned J.C., 2005 *Nucl. Phys. B (Proc. Suppl.)* **143** 152