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Signal imaging from S^3 — 80-channel detector of reactor antineutrinos

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ABSTRACT: A nuclear power reactor is the most intense man-controlled source of electron antineutrinos. An installation of a neutrino detector in close vicinity to a reactor core (~10 m) enables the study of neutrino properties with a higher efficiency, for example an investigation of short-baseline neutrino oscillations and a verification of sterile neutrino hypothesis. A knowledge of the antineutrino flux enables us to determine the reactor power in real time. Measurement of the antineutrino energy spectrum gives the possibility to investigate the isotopic composition of the reactor fuel and to monitor illegal manipulation of ^{239}Pu. The S^3 detector was developed as a common effort between IEAP CTU in Prague and JINR (Dubna). The high segmentation of the detector enables identification of the antineutrino interaction which has a specific time, energy and spatial pattern. The software for the data acquisition and visualization is under development in IEAP CTU in Prague. Since the detector does not contain any flammable, toxic, caustic and dangerous materials, it is safe to be installed under the industrial power reactor. The S^3 detector has applications in fundamental physics, an applied research as well as nuclear safety.

KEYWORDS: Interaction of radiation with matter; Neutrino detectors; Scintillators and scintillating fibres and light guides; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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Contents

1 Introduction

Neutrinos are one of the most interesting and widespread particles in the Universe. The experimental study of neutrinos started in the 1950s [1] and has not been thoroughly explored up to the present day.

Neutrinos are elementary subatomic particles which are produced in a wide variety of nuclear processes. Since neutrinos interact only via the weak interaction, their penetration through material is extremely high. Therefore, we need large-volume detectors or intense sources of neutrinos. Nuclear power reactor is one of the most intensive man-controlled source of pure electron antineutrinos. Electron antineutrinos are produced in β-decays of neutron-rich fission fragments created in fission reactions. About six electron antineutrinos are produced in one fission process. Since the antineutrino flux decreases with a distance as $\sim d^2$, it is most effective to install a detector as close to the reactor as possible.

The new experiment S^3 devoted to the study of reactor antineutrinos was designed and constructed as a common activity of IEAP CTU in Prague and JINR (Dubna). The S^3 detector (40 x 40 x 40 cm^3) is a highly-segmented polystyrene based scintillating detector composed of 80 detector elements (40 x 20 x 1 cm^3). The idea of the S^3 detector is inspired by the DANSS detector [2], which was built in JINR and is located in the nuclear power plant in Udomlya. The S^3 detector is planned to be used as a reference detector measuring the antineutrino flux at a fixed distance from the reactor while the distance of the DANSS detector is variable. Since the S^3 detector meets very strict safety rules of the nuclear power plant, it can be installed close to the reactor ($\sim$ 10 m). This short distance allows us to study neutrino properties with higher efficiency, investigate short-baseline neutrino oscillations and experimentally verify the sterile neutrino hypothesis. Construction of the S^3 detector can be also of great importance for other research objectives. The S^3 detector can be used for reactor monitoring in real time, determination of isotopic composition of the fuel [3] and scanning of illegal extraction of ^{239}Pu (essential part of nuclear weapons). Neutrinos easily penetrate through the material surrounding the reactor core. Therefore, the S^3 detector has a big advantage in comparison with standard monitoring devices based on a detection of neutrons from the reactor.

2 Detection technique

An inverse beta decay (IBD) was historically the first reaction, in which an electron antineutrino was detected by C. Cowan and F. Reines in 1956 [4]. The IBD is based on the interaction of an electron antineutrino with a proton in a detector, in our case a plastic scintillator (rich in hydrogen). A positron and a neutron are produced in this interaction:

$$\tilde{\nu}_e + p \longrightarrow n + e^+. \tag{2.1}$$

The positron deposits its energy in a very short range and annihilates with an electron giving out two 511-keV gammas at 180° in Center of Mass System of the electron-positron pair. This process is a source of a prompt signal. The prompt energy, deposited by the positron including the annihilation energy, is related to the initial energy of the antineutrino as [5]:

$$E_{\text{prompt}} = E_{\tilde{\nu}_e} - 0.78\, MeV \tag{2.2}$$

The neutron from the IBD propagates in the direction of the antineutrino thus providing information about the antineutrino momentum. The neutron is moderated in material by the scattering on the hydrogen and is captured on a neutron converter (Gd in our case) a few microseconds after the positron interaction. The Gd nuclei undergoes deexcitation with the emission of few gammas with the total energy of 8 MeV. This process is a source of a delayed signal. The signature of the IBD is an occurrence of a prompt signal from the positron and a delayed signal from the neutron interaction. According to simulations the time interval between these two signals is in the range of 2-100 µs, but most events occur between 2-50 µs.

The IBD interaction has the unique time and the spatial pattern and should be well-recognized due to the high segmentation of the S^3 detector.

3 S^3 detector — description and characteristics

A basic detector element (40 x 20 x 1 cm^3) of the S^3 detector is a plastic scintillator based on a polystyrene matrix. The polystyrene matrix is doped with a primary dopant p-terfenyl (2.0 wt%) and a wavelength shifter 1,4-bis(5- phenoloxazol-2-yl) benzene (0.025 wt%) known as POPOP. This chemical composition was derived during tests of different concentrations of both luminescent additives in the polystyrene matrix and is optimized for a given shape of the detector element [6]. The detector elements were manufactured by NUVIA, a.s. [7]. The uniform light collection along the detector element is done using 19 Kuraray Y-11(200) wavelength-shifting fibers [8], which are glued into 19 grooves. Distance between two neighboring grooves is 1 cm, which ensures optimal light collection from the scintillator. Each detector element is covered by 4 layers of the 200 µm teflon tape used as a reflective wrapping material.

The whole S^3 detector consists of 80 detector elements. One layer of the detector is constituted by two detector elements touching with the longest side. Two detector elements from the next layer lie perpendicularly to detector elements from the previous layer thus forming X-Y structure. There is a layer of Gd_2O_3 between each two neighboring layers used as converter of thermal neutrons. The S^3 detector is shown in figure 1.

The S^3 detector is surrounded by a complex shielding ensuring the suppression of the gamma and the neutron background, see figure 2. The shielding consists of (from the inside):

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Figure 1. The S^3 detector consisting of 80 detector elements.

- 10 cm of 100-years old lead shielding in forms of bricks and bars,
- 8 cm of borated polyethylene,
- 16 cm of standard polyethylene.

(a) Lead shielding.

(b) Complete shielding.

Figure 2. A step-wise construction of the shielding for the S^3 detector — the complete lead shielding (a) and the complete lead and polyethylene shielding (b). The shielding was tested in an underground civil protection shelter Bezovka located in Prague.

Fast neutrons represent the main source of background, because they can mimic IBD interactions — the prompt signal is caused by the neutron thermalization and the delayed signal is caused by the neutron capture on the neutron converter. Efficiency of the neutron shielding was tested using an AmBe neutron source. Based on the results of this test the thickness of the standard polyethylene shielding was increased to 16 cm [9].

The low-energy part of the energy spectrum is important due to the detection of low energies from 511-keV gammas from the positron annihilation. Their identification could be complicated because gammas interact with a low-Z material mainly via the Compton scattering depositing only part of their energy in the material. Therefore, the signal from 511-keV gammas can be hidden in the background. Using the shielding designed for the S^3 detector the background was suppressed by a factor of 28.5 resulting in 4.56 events/s in the low energy part up to 3 MeV. This result represents convenient conditions for the detection of 511-keV gammas. The measurement was carried out in

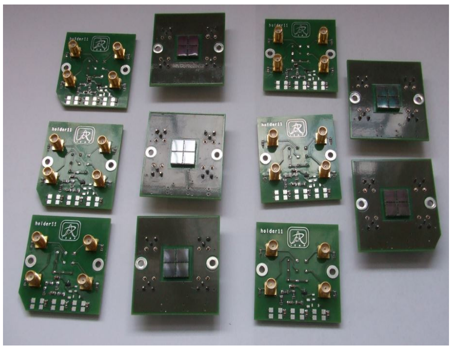
Table 1. Number of events per second up to 3 MeV detected in each phase of the shielding installation.

	Without shielding	Lead shielding	Polyethylene and lead shielding
Counts/s	130.10 ± 11.40	5.27 ± 2.29	4.5 ± 2.12

the civil protection shelter Bezovka. The results of testing measurements with different shielding materials are summarized in table 1.

4 Data acquisition system

Light produced by each detector element is collected via 19 WLS fibers to SensL Silicon Photomultipliers (SiPM), which ensures transformation of light into an electric signal. Light collection is done for each detector element individually thus producing the 80 channel system. PCB boards with four SiPMs are shown in figure 3.



(a) PCBs from both sides.

(b) PCBs on detector.

Figure 3. Both-sided view on PCBs with SensL SiPMs (a) and location of PCBs on the detector (b).

Signal from each SiPM is fed to an amplifier/shaper. Output from the amplifier/shaper is input to a fast ADC (24 channels, 15 bits, 100 MS/s). The detailed view of the block of six amplifiers/shapers and the fast ADC is shown in figure 4.

The 24-channel fast ADC is intended for tests. An 84-channel fast ADC was developed for data acquisition for the whole 80-channel S^3 detector and 4-channel cosmic veto system. For the real-time visualization of signals and DAQ from the S^3 detector software (SW) has been developed and tested. It consists of:

- the control window for individual channel configuration, information about the status of channels and data export,
- the imaging window for the real-time visualization of a signal from each channel,
- the imaging window for the visualization of amplitude spectra.

An illustration of the developed software is shown in figure 5.

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(a) Amplifiers. (b) Fast ADC. (c) Fast ADC in operation.

Figure 4. Detailed view of the block of 6 amplifiers/shapers (a), the 24-channel fast ADC with amplifiers/shapers (b) and fast ADC with connected signal cables and monitor displaying pulses from the S^3 detector (c).

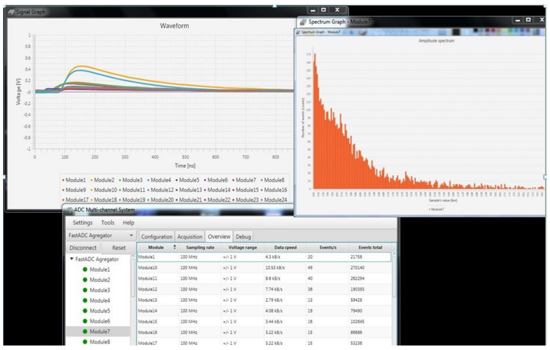

Figure 5. Software with three windows — control window showing status of each channel, two imaging windows showing signal and amplitude spectra from each channel.

The software described is for the control of electronics and data acquisition in real time. Therefore, functionality of the whole S^3 detector has to be checked regularly (e.g. time resolution among all channels). The software for the S^3 experiment can be classified as a very demanding application, especially if higher graphic complexity typical of Windows is required. The big advantage of such a software system is that it can help to discover problems during the measurement, e.g. hardware failure and incorrect channel setting, before offline data analysis.

A time accuracy error can be demonstrated from a histogram of time shifts. Construction of the time shift histogram is based on searching for coincidences from two channels in a small time window (500 ns and less), in which mainly coincidences of cosmic muons are expected. If there is a coincidence in each channel in a given time window then the time between events is determined and this value is plotted in the histogram. Since muon events occur almost simultaneously in both channels, we expect a distribution around zero. In case the time shift distribution is shifted from zero it means incorrect timing caused by hardware failure, incorrect channel setting, failure of an amplifier or an incorrect transport of a data package. An example of the time shift distribution for the correct case (most cases) and the incorrect case for a pair of selected channels is shown in figure 6. One bin corresponds to 10 ns. The measurements were carried out at the standard IEAP CTU laboratory.

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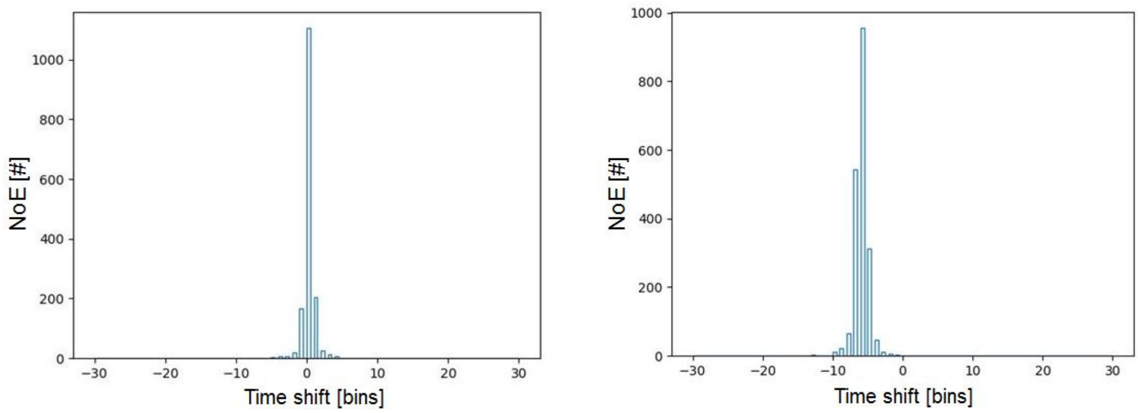

(a) Correct case — zero time shift.

(b) Incorrect case — non-zero time shifts.

Figure 6. An example of the correct case (a) and the incorrect one caused by corrupted data (b).

Measured results show that our multichannel system is very precise in timing, which is an essential requirement for searching for neutrino-like events.

5 Background measurement

The high segmentation of the S^3 detector is a big advantage because of the specific time, energy and the spatial pattern of the IBD interaction. According to simulations [10] an energy from the positron produced in the reaction (2.1) is deposited in ~70% in one detector element and in ~30% in two detector elements. The total energy of 8 MeV from the deexcitation of a Gd nucleus after the neutron capture is distributed among 1-12 gammas thus producing a signal in few detector elements. The signature of the neutrino-like event in the S^3 detector was defined as the occurrence of the prompt signal in one or two detector elements and the delayed signal occurring in at least two detector elements in the delayed coincidence (~2-50 μs).

A distribution of prompt versus delayed energies is shown in figure 7. Since the S^3 detector is now in the testing phase, more probable cases with a prompt signal in one detector element and delayed signal in two and more detector elements were not analyzed due to a high background. For the purpose of the visualization less probable cases with the prompt signal in just two detector elements and the delayed signal in more than two detector elements are searched in a 100 μs time window. Two 511-keV gammas from the positron annihilation are not considered in this analysis.

It should be emphasized that the S^3 detector is located at the laboratory and is not exposed to a flux of antineutrinos under a reactor. Therefore, the probability of an occurrence of the IBD event is negligible. During a two day measurement an IBD event was not detected. Coincidences shown in the figure 7 are mainly caused by random coincidences of cosmic muons or neutrons. However, this measurement proved the possibility of the detection of neutrino-like events by the S^3 detector.

6 Summary

First measurements using the 80-channel S^3 detector verified the functionality of the proposed detector design and electronics. The data acquisition system of the S^3 detector can be classified as

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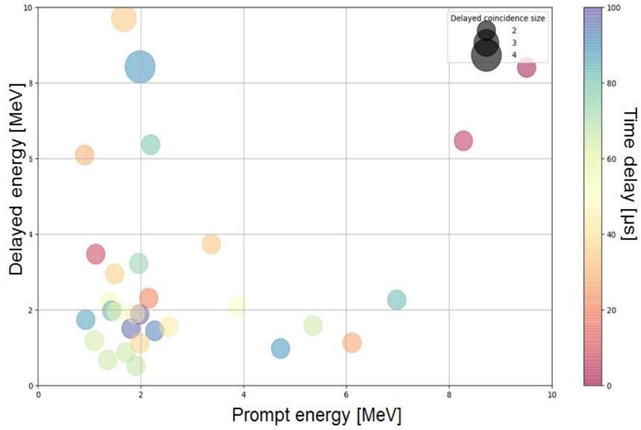

Figure 7. The distribution of the prompt versus the delayed energy. The color of the blob indicates the time interval between the prompt and the delayed signal. The size of the blob corresponds to the number of detector elements which give signal in the delayed coincidence. Events with the prompt signal in two detector elements are considered.

a complicated multichannel system working in real-time and with fast signals (rise time ~1.7 ns) from a plastic scintillator. Results presented in this paper showed that the S^3 detector is fit for the purpose. Moreover, the S^3 detector meets very strict safety rules of the nuclear power plants and can be installed in a chamber located immediately under the reactor. Estimation of the IBD detection by the S^3 detector is ~300 antineutrino events per day. The close vicinity from the reactor enables us to study neutrino properties with a higher efficiency, to investigate neutrino oscillations at short baselines and try to verify the hypothesis of a sterile neutrino. Since antineutrinos produced in the nuclear processes in the reactor fuel penetrate the reactor vessels and other reactor materials almost without an interaction, they can be also used as a reliable monitor of the reactor processes. Therefore, the S^3 detector can be used for the real-time measurement of the reactor power, determination of fuel burnout and control of the illegal extraction of ^{239}Pu.

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