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Design and first tests of the S^3 detector of reactor antineutrinos

Mária Slavíčková[1,2], Vyacheslav Belov[4], Jan Broulím[1], Victor Brudanin[4], Viatcheslav Egorov[4],
Lukáš Fajt[1],Maria Fomina[4], Rastislav Hodák[1], Sergei Kazartsev[4], Zdeněk Kruliš[3], Miroslav Macko[1],
Petr Mašek[1], Danuše Michálková[3], Maroš Petro[1], Petr Přidal[1], Ekaterina Rukhadze[1], Egor Shevchik[4],
Karel Smolek[1], Tomáš Slavíček[1], Ivan Štekl[1], and Igor Zhitnikov[4]
[1]Institute of Experimental and Applied Physics, CTU in Prague, Czech Republic
[2]Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague, Czech Republic
[3]Institute of Macromolecular Chemistry, Czech Academy of Sciences, Czech Republic
[4]Joint Institute for Nuclear Research, Dubna, Russia
maria.slavickova@utef.cvut.cz

Abstract—**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 is a compact, highly segmented polystyrene-based scintillating detector composed of 80 detector elements with a gadolinium neutron converter between elements layers. A positron and a neutron are produced in an inverse beta decay initiated with an electron antineutrino in the detector. A modular multi-channel fast ADC was developed for the data acquisition for the whole 80-channel S^3 detector and the 4-channel cosmic veto system. The detector meets very strict safety rules of nuclear power plants and can be installed in a chamber located immediately under the reactor. The close vicinity from the reactor enables 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. The details of the design and construction of the S^3 detector, as well as properties of the modular multi-channel fast ADC system, and first tests of the device are presented.**

***Keywords* — S^3 experiment, reactor neutrinos, neutrino oscillations.**

I. INTRODUCTION

NUCLEAR power reactor is one the most intense man-controlled source of the pure electron antineutrinos. A typical 3 GW$_{\text{th}}$ (e.g. VVER-1000 in Temelin, CZE) nuclear power reactor emits about 10^{21} electron antineutrinos/s/4π. Since the antineutrino flux decreases with a distance as $1/d^2$, it is important to install the detector as close from the reactor as possible or construct a large-volume detector. However, safety rules of a nuclear power plant do not allow any flammable, toxic, caustic or other dangerous materials in the reactor building.

The aim of the S^3 experiment [1], [2], [3] was to construct a compact antineutrino detector, which does not contain dangerous materials and can be installed in the reactor building. Such detector could contribute to the investigation of the neutrino oscillations at very short baselines (~m) and verification or rejection of the sterile neutrino hypothesis. Moreover, such detector could be used in an applied research for the real-time measurement of the reactor power, determination of fuel burnout process and control of the illegal manipulation with ^{239}Pu. Furthermore, antineutrinos penetrate all building materials practically without the interaction and carry direct information about processes taking place in the reactor core. Therefore, the S^3 detector could be an ideal candidate to be a monitoring device of the reactor core.

An idea to develop the S^3 detector is based on the DANSS detector (1 m x 1 m x 1 m) [4], which was constructed in JINR, Dubna. The DANSS detector is a highly-segmented polystyrene based scintillating detector, which consists of 2500 scintillating elements (4 cm x 1 cm x 100 cm). It is installed on a movable platform thus measuring the antineutrino flux at different positions from the reactor. The antineutrino flux is not constant at different positions from the reactor and changes in time with the change of the reactor power and isotopic composition. Therefore, it was decided to develop a reference detector measuring the antineutrino flux at a fixed position from the reactor. As a result, two S^3 detectors were constructed. The first S^3 detector together with a complex shielding and DAQ system is situated at IEAP CTU in Prague and is planned to be installed in Temelin Nuclear Power Plant in Czech Republic. Simultaneously, the second S^3 detector is constructed in JINR, Dubna. It will be used as a reference detector measuring the reactor antineutrinos at a fixed position from the reactor while the position of the DANSS detector will change.

II. DETECTION TECHNIQUE

A detection principle of the S^3 detector is based on the inverse beta decay interaction, where an antineutrino emitted from the reactor core interacts with a proton in the detector volume and a neutron and a positron are created:

$$\overline{\nu_e} + p \longrightarrow n + e^+ \qquad (1)$$

The positron losses its energy in a very short range and annihilates with an electron producing two 511 keV gammas at 180° in the Center of the Mass System of the electron and positron pair. The neutron is moderated by the scattering on a hydrogen atom and then captured on a neutron converter, in our case gadolinium. The gadolinium nucleus comes into an excited state and deexcites with the emission of gamma quanta with the total energy of 8 MeV and within 20 cm radius. As a result, the inverse beta decay interaction can be detected as a prompt signal from the positron interaction and annihilation gammas and a delayed signal from the neutron capture. The time interval between the prompt and the delayed signal is expected to be 2 – 50 μs.

The kinetic energy of the positron T_{e^+} is related to the energy of the incoming antineutrino $\mathrm{E}_{\overline{\nu_e}}$ [5] as:

$$\mathrm{T}_{e^+} \approx \mathrm{E}_{\overline{\nu_e}} - 1.806\ \mathrm{MeV}. \qquad (2)$$

Therefore, we can reconstruct the energy of the incoming antineutrino by the measurement of the prompt signal.

The neutron produced in the inverse beta decay interaction propagates in the direction of the incoming antineutrino thus providing information about the momentum of the antineutrino.

High segmentation of the detector enables us to suppress the background as well as identify very characteristic time and spatial pattern of the antineutrino interaction in the detector.

III. EXPERIMENTAL SETUP

The S^3 detector (40 cm x 40 cm x 40 cm), see Fig. 1, consists of 80 pieces of polystyrene-based scintillating elements (40 cm x 20 cm x 1 cm each) produced by the NUVIA, a.s. [6]. The polystyrene matrix is doped with 2.0% p-terfenyl (pTP) and 0.025% of 1,4-bis(5- phenyloxazol-2-yl) benzene (POPOP) [7]. This concentration of dopants ensures 1.4 times better light output in comparison with scintillators standardly manufactured by the NUVIA, a.s.

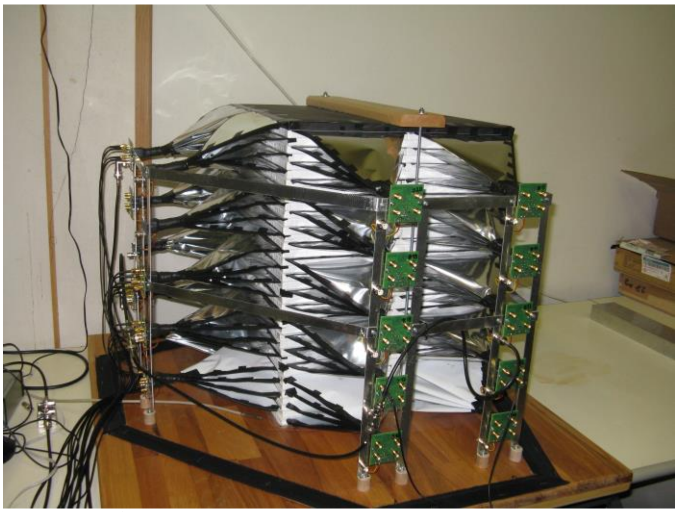

Fig. 1. The S^3 detector consisting of 80 scintillating elements.

Each scintillating element is covered by the 800 μm thick Teflon layer working as a reflective material. The Teflon layer ensures 1.6 times better light yield in comparison with the bare scintillator and 80% homogeneity of the light collection along the scintillating element. Scintillating elements are arranged in the detector so that each layer (2 elements) lies perpendicularly to the previous one thus forming X-Y structure. Between each two layers there is a neutron conversion layer based on Gd_2O_3, which was prepared in cooperation with IMC of Czech Academy of Science.

Light collection along the scintillating element is done using 19 Kuraray Y-11(200) wavelength-shifting fibers [8], which are glued into grooves by the optical epoxy glue. A distance between two neighboring grooves is 1 cm, which ensures an uniform light collection. Light produced in the scintillating element after the particle interaction is guided via wavelength-shifting fibers to the 6 mm x 6 mm SensL SiPM, where the light is converted to an electric signal. The PCB with four pieces of SensL SiPMs, which collect signals from four individual scintillating elements, is shown in Fig. 2a. The location of the PCB on the S^3 detector is shown Fig. 2b.

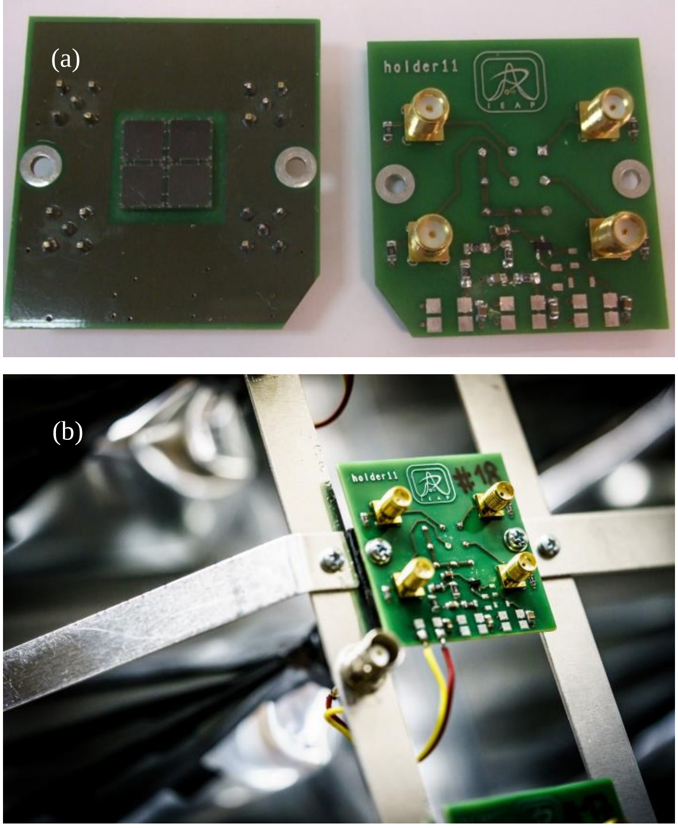

Fig. 2. The both-sided view on the PCB with four pieces of SensL SiPMs (a) and the position of the PCB with SiPMs on the S^3 detector (b).

A big advantage of the front-end electronics is its negligible power consumption (maximal value of 1.7 W). This eliminates any need of cooling, even if the detector is located in a complex shielding. Electric signal from the SiPM is amplified and shaped by the signal shaping module (shaping constant is 1 μs), which is shown on the left part of Fig. 3. The signal shaping module is mechanically connected with the ADC module, see the right part of Fig. 3. The amplified and shaped signal is processed in a modular multichannel fast ADC, which consists of 84 ADC modules (15 bits + bit for a sign, 100 MS/s @ 84 channels). This multichannel system was designed and constructed at IEAP CTU in Prague and it is used for the data acquisition from the whole 80-channel S^3 detector and the 4-channel cosmic muon veto.

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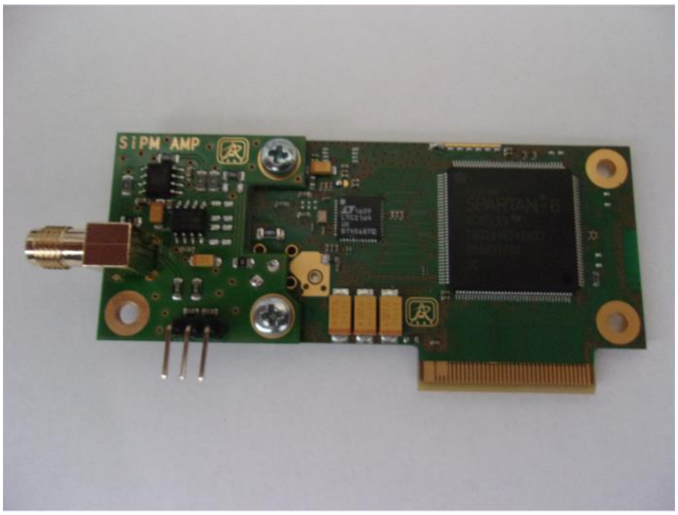


Fig. 3. The signal shaping module (left) attached to the ADC module (right).

The front and back view on the 84-channel digitizer is shown in Fig. 4a and Fig. 4b.

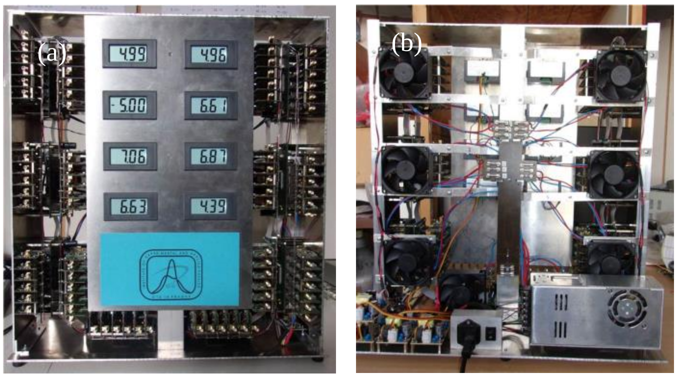
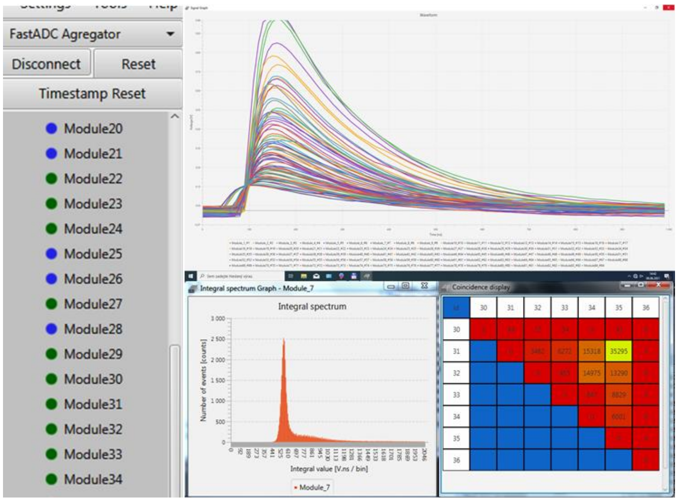


Fig. 4. The Front (a) and back view (b) on the 84-channel digitizer.

After exceeding the threshold, the analog signal is digitized with the sampling rate of 100 MHz and with the required number of samples. Each event has a timestamp counted with a step of 10 ns. The digital signal is then sent to a PC using USB2 (max 480 Mb/s), where it is processed by the DAQ software developed by IEAP CTU in Prague. The DAQ software enables:

- individual configuration of each channel,
- information about the status of each channel,
- real-time visualization of the signal from each channel,
- real-time visualization of energy spectrum from each channel,
- visualization of coincidences,
- data export.

An illustration of the DAQ software is shown in Fig. 5. For clarity, not all functions of the DAQ software are shown.



[illegible]	30	31	32	33	34	35	36
30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
31		[illegible]	[illegible]	[illegible]	15318	35295	[illegible]
32			[illegible]	[illegible]	14975	13290	[illegible]
33				[illegible]	[illegible]	8829	[illegible]
34					[illegible]	6001	[illegible]
35						[illegible]	[illegible]
36							[illegible]

Fig. 5. The DAQ software showing information about the status of each channel (left), signals from 80 channels, energy spectrum from one chosen channel and number of coincidences between two channels.

The whole experimental setup consisting of the detector part and DAQ system is shown in Fig. 6.

Fig. 6. The experimental setup consisting of the detector part and the DAQ system. The S^3 detector is surrounded by a black light-tight box (right).

The S^3 detector is surrounded by a complex shielding consisting of (from inside of the detector):

- 10 cm of 100 years old lead shielding in form of bricks and bars,
- 8 cm of polyethylene with 3.5% admixture of boron,
- 16 cm of standard polyethylene.

Lead shielding was designed to suppress the low energy background, in which the signal from two 511 keV gammas from the positron annihilation can be hidden. The low-energy part was suppressed to 4.5 ± 2.1 events/s using the shielding [1], which provides ideal conditions for the measurement of 511 keV gammas. The lead shielding is shown in Fig. 7a. The polyethylene shielding is used to suppress fast neutrons, which can mimic the antineutrino interaction – the prompt signal from the neutron thermalization and the delayed signal from the neutron capture on gadolinium. The complete shielding is shown in Fig. 7b. The effectivity of the shielding was measured in the civil protection shelter Bezovka (45 m w. e.) located in Prague.

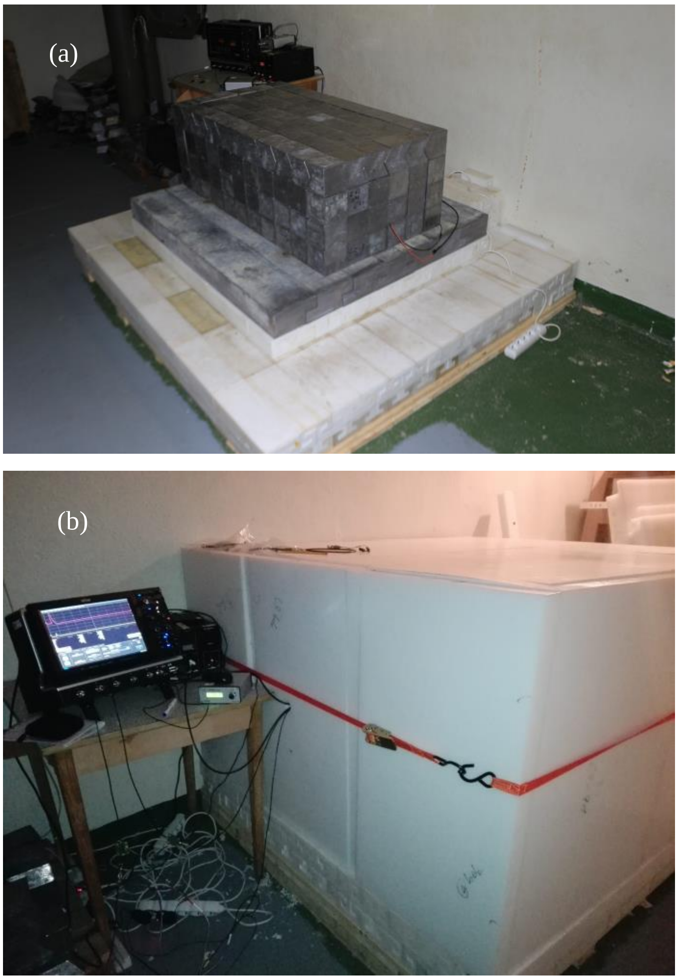


Fig. 7. Lead shielding with a bottom layer of the polyethylene shielding (a) and complete lead and polyethylene shielding (b).

IV. DETERMINATION OF THE TRESHOLD SENSITIVITY OF THE S^3 DETECTOR

For better identification of the inverse beta decay interaction caused by an antineutrino, the detection of two 511 keV gammas is important. However, 511 keV gamma interacts mainly via the Compton scattering in the plastic scintillator depositing only part of its energy in the detector. In some cases, the analysis could be complicated because the low-energy events from 511 keV gammas are hidden in the noise of the SiPM. To distinguish physical events from the electronics noise, analysis of the SiPM self-noise was done. The measurement was performed in a light-tight box while the scintillating element was not connected to the sensitive area of the SiPM. Therefore, only the self-noise of the SiPM was detected. The single photoelectron spectrum of the FC60035 SiPM is shown in Fig. 8. Values obtained during the fitting of the photoelectron peaks are shown in Table I. Based on this measurement, the energy threshold was determined. To demonstrate that the threshold was determined properly the measurement of the physical events was carried out after the connection of the scintillating element to the sensitive area of the FC60035 SiPM. Both measurements were performed under the same conditions, i.e. bias current of the SiPM was 6 μA, the same amplification and shaping were used.

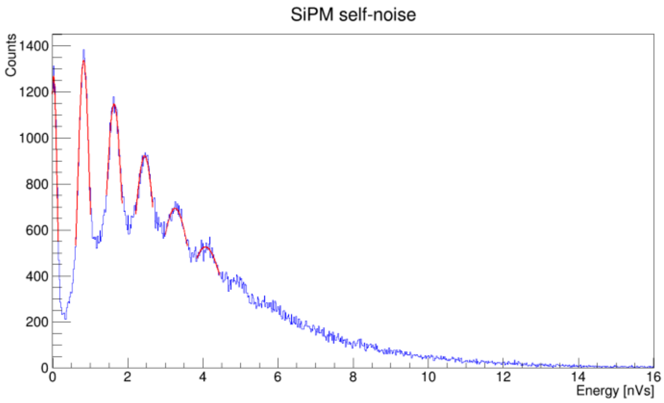


Fig. 8. An example of the photoelectron spectrum of the FC60035 SiPM (blue line) measured at 6 μA and fitted photoelectron peaks (red line).

TABLE I
FIT VALUES OF THE PHOTOELECTRON PEAKS

Number of p.e.	Mean [nVs]	Error [nVs]	Distance between neighboring p.e.
0	0.002	0.001	-
1	0.799	0.002	$\Delta_{10} = 0.797$
2	1.608	0.003	$\Delta_{21} = 0.809$
3	2.431	0.005	$\Delta_{32} = 0.823$
4	3.238	0.010	$\Delta_{43} = 0.807$
			$\bar{\Delta} = 0.820$

Fig. 9 shows the measured pulse-height spectrum which consists of two parts. The red line corresponds to the SiPM self-noise, which is shown in Fig. 8, in detail. The blue line represents physical events induced mainly by the gamma and cosmic muon background.

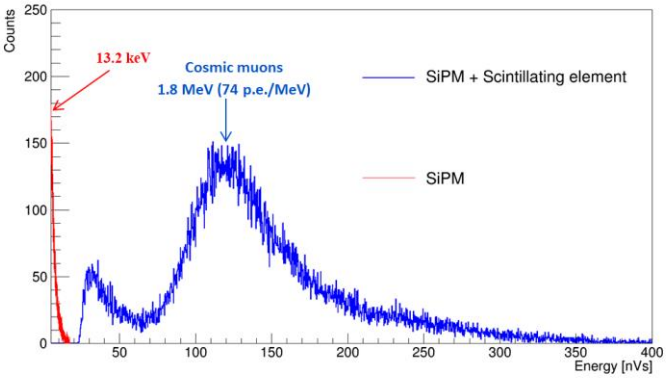


Fig. 9. An example of the spectrum. Red line corresponds to the SiPM self-noise. The blue line represents the pulse-height spectrum of the physical background – the gamma and cosmic muon background.

It is evident that the SiPM self-noise is well separated from the scientific data. Based on the Monte Carlo simulation, the peak in the background spectrum (blue line) corresponds to cosmic muons with the energy of 1.8 MeV and gives the light gain of 148 photoelectrons (p.e.). Therefore, the light gain of one scintillating element is 70-75 p.e./MeV. The maximum of the SiPM self-noise is at 13.2 keV corresponding to the first p.e. and the amount of noise events decreases to 1/2 at the energy of 50 keV. This analysis showed that the threshold sensitivity of the detector is about 50 keV and low-energy events from the antineutrino interaction could be well identified.

V. DETECTOR CALIBRATION

The calibration of each scintillating element of the S^3 detector is done by the use of cosmic muons. When muon penetrates the scintillating element, it behaves like a minimum ionizing particle and deposits 1.8 MeV of its energy per each 1 cm of its track. Fig. 10 presents the amplitude (left) and the energy (right) spectrum from a selected scintillating element. If all collected events are used for the histogram construction, see Fig. 10a, the muon peak is almost invisible. If the events with 5 or more hit scintillating elements are selected for the histogram construction, see Fig. 10b, the noise is suppressed, the muon peak is clear, and it can be used for the energy calibration.

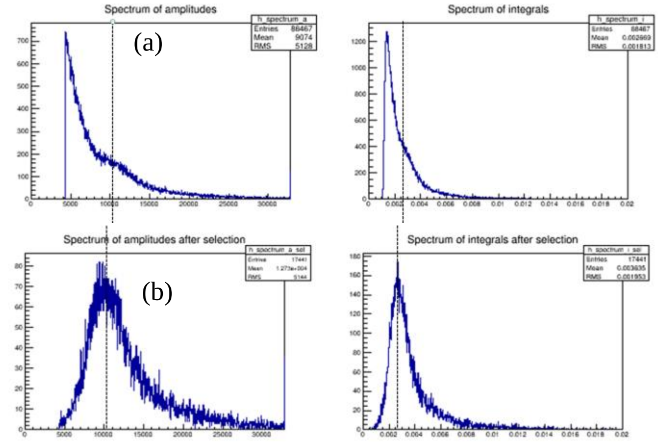


Fig. 10. The amplitude and the energy spectrum from one scintillating element before (a) and after (b) the selection of events with penetrating muons (events with more hitting scintillating elements).

VI. CONCLUSIONS

The S^3 detector represents a compact antineutrino spectrometer, which does not contain any dangerous material and can be installed in the building of the nuclear power plant. The big advantage of the detector is its affordable price, user friendly DAQ software and low demands on number of staff. The multichannel digitizer was designed and constructed to measure in real time and with fast signals from plastic scintillators.

At present, the S^3 detector is tested and calibrated in the IEAP CTU laboratory and is planned to be installed in the Bezovka civil protection shelter to perform a long-term stability tests. Moreover, MC simulations were carried out to optimize the selection criteria for the reactor antineutrino events. All such results are planned to be experimentally verified. Because the S^3 detector is located in the laboratory and is not exposed to the flux of antineutrinos from the reactor, we need to carry out tests using fast neutrons, which can mimic antineutrino interactions.

After tests of long-stability and measurements with radiation sources, the S^3 detector is planned to be installed in the Temelin Nuclear Power Plant, where it will be used for the investigation of the neutrino properties and reactor monitoring in a real time. The second S^3 detector is constructed in JINR, Dubna and is planned to be used as a reference detector for the DANSS experiment.

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