Development of Japanese-style cosmic-ray muon detector for outreach and education

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For many citizens and students interested in particle physics and astrophysics, there are few opportunities to touch real research that needs expensive equipment such as an accelerator, a telescope, and a detector. However, recent technological developments have made it possible to build a low-cost detector, and some physicists have tried to develop simple detectors for outreach and education. We have also designed and developed a low-cost and compact detector, OSECHI (Outreach & Science Education Cosmic-ray Hunting Instrument), that can measure cosmic-ray muons. The detector consists of three 3D-printed plastic scintillator layers that can measure coincident events by one detector. Silicon photomultipliers (SiPMs) are mounted on the scintillators for light collection. Output signals from SiPMs are read by a custom-designed electronics board which records the charge and timing information of the signals. Three LEDs corresponding to three scintillators are implemented on the board, and we can check the signals by eye in real time. The board can be powered by a USB connector and has the DC-HV converter to provide the bias voltage to the SiPMs. Some interfaces are implemented in which commercial monitors such as thermometers and GPS can be added. The functionalities for all signal processing are controlled by a chip microcontroller. All the parts of the detector are contained in the Japanese-style tiered bento box, "Jubako". In this paper, we introduce the details of the OSECHI and the performance of the prototype. Examples of its use of outreach will also be reported.

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1. Introduction

There is a significant interest among many citizens and students in the fields of particle physics and astrophysics. However, the costs and the size associated with the equipment such as accelerators, telescopes, and detectors often make it difficult for many people to participate actively. There is a growing need for the development of affordable and compact detectors specifically designed for outreach purposes. On the other hand, recent technological developments have made it possible to build a low-cost and compact detector. Some physicists in the world have tried to develop simple detectors or applications for outreach and education, for example Cosmic Watch (CW)[1], Distributed Electronic Cosmic-ray Observatory (DECO)[2], and so on.

In Japan, some researchers including us launched an outreach and education framework called Tan-Q[3], in which those physicists and university students support physics and its related research for junior and high school students. In addition, Tan-Q sometimes holds workshops for not only students but also citizens to provide short programs of physics experiments. For both activities, the low-cost and compact detector is indispensable and CW is mainly utilized[4, 5]. In parallel, we have also designed and developed a low-cost and compact detector, OSECHI (Outreach & Science Education Cosmic-ray Hunting Instrument), as a project in Tan-Q. Students can also join this project and it gives good opportunities to touch real detector development. All the parts of the detector are contained in the Japanese-style tiered bento box, "Jubako", such as the traditional Japanese New Year's cuisine, "OSECHI".

In this paper, we provide a detailed description of the design and development of our affordable and compact detector, OSECHI. Then, we present the current status of performance evaluations. The potential applications of this detector in educational settings, outreach activities, and citizen science initiatives are also described.

2. Detector design

2.1 Whole design

Figure 1 shows the whole design for the current version of OSECHI. The detector consists of three scintillators that can measure coincident events by one detector. For light collection, silicon photomultipliers (SiPMs) are mounted on the scintillators with the support structures. Output signals from SiPMs are read by a custom-designed electronics board which records the charge and timing information of the signals. Three LEDs corresponding to three scintillators are implemented on the board, and we can check the signals by eye in real time. The board can be powered by a USB connector and has the DC-HV converter to provide the bias voltage to the SiPMs. Some interfaces are implemented in which commercial monitors such as thermometers and GPS can be added. The functionalities for all signal processing are controlled by a chip microcontroller. Scintillators and SiPMs are contained in the bottom layer of Jubako. Electronics boards (PCBs) are put in the upper layer of Jubako. The SiPMs and the PCBs are connected via cables through a hole in the bottom of the upper layer. The hole and the gap between the upper and bottom layers are shielded by black electrical tape for optical isolation of the scintillators.
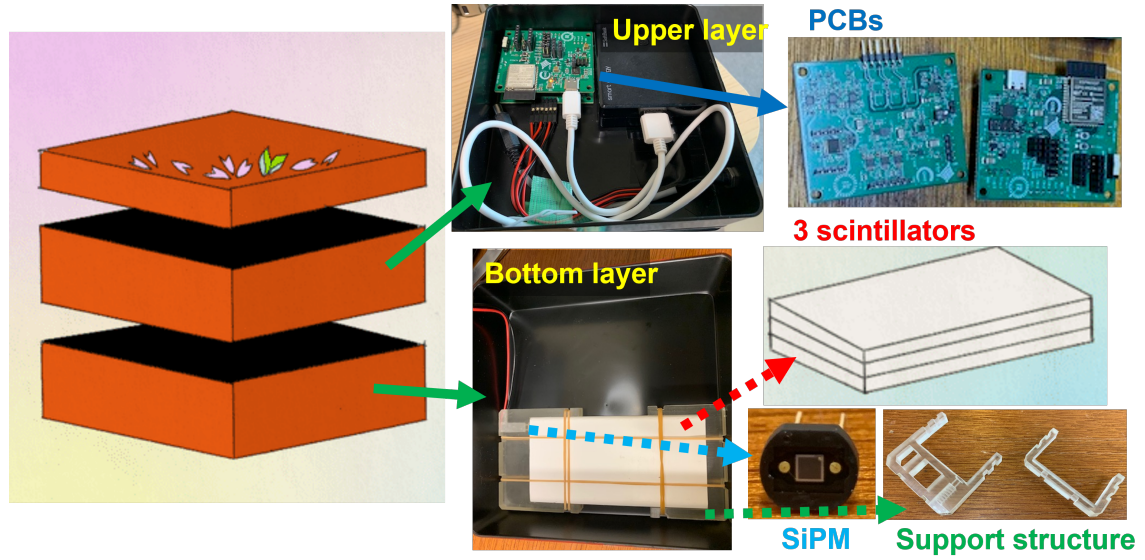
Figure 1: Japanese-style cosmic-ray muon detector, OSECHI.

2.2 Bottom layer

In the bottom layer, the main detector system composed of three scintillators, three SiPMs, and those support structures is installed. For the scintillator, the plastic scintillator (Eljen EJ-200) with the size of 1 cm × 5 cm × 10 cm is adopted as a prototype. In order to maximize the light collection for each event, the whole area of the scintillator except for the photon readout region is wrapped with the Teflon tape as a reflector. As a photon readout SiPM, MPPC (HAMAMATSU S13360-1350CS) is adopted due to its performance, compactness, and cost. SiPMs are mounted on the original support structure made by 3D printer. The surface of the SiPMs is aligned with the inner surface of the support structure and can be in close contact with the scintillators. For efficient light collection, the SiPMs are coupled to the scintillators with optical grease. The scintillator is sandwiched between two support structures and fixed with rubber bands. The scintillators are arranged in three layers as shown in Figure 1.

For cost reduction, the use of 3D-printed scintillators, which have recently been developed[6], is being promoted in parallel. If this is achieved, a cost reduction of 1/10 for the detector part would be expected.

2.3 Upper layer

Two PCBs are located in the upper layer. These boards perform the data acquisition and signal processing. Two boards are named Readout Board (R-Board) and Control Board (C-Board).

R-Board consists of the signal read-out circuit and SiPM bias voltage circuit. In the R-Board, the output signal from SiPMs is input to the amplification circuit which uses a low-cost high-performance op-amp, JRC NJM2712. The amplified signal branches into two paths. One path is to the comparator (STMicroelectronics TS864IPT). The threshold of the comparator is fed by DAC (Microchip MCP4811) which is controlled by the microcontroller on C-Board. The output signals of the comparators are sent to the C-Board and these signals are used for the trigger of the

data taking and the timing information of the event. The other paths are directly to the C-Board and these signals are used for the charge information. As a SiPM bias voltage circuit, DC-HV converter (Analog Devices LT3482) is implemented. Potentiometers are also implemented to adjust the SiPMs operation voltages before the measurement. The power for each chip is provided by regulators (ON Semiconductor CAT6243, Texas Instruments TLV75901, LM27761) on R-Board, which make 3.3 V, 2.5 V, and -2.5 V from main power of 5 V fed by C-Board.

C-Board consists of the microcontroller, peak-hold circuit, and some interfaces. The board can be powered by a USB connector. This power of 5 V is supplied not only for C-Board but also for R-Board. As the microcontroller, Espressif Systems ESP-WROOM32 (ESP32) is used, which has not only the functions of microcontroller but also network modules. Its code can be written with Arduino code. ESP32 has the 12 bit ADC, 8 bit DAC, and some interfaces (GPIO, SPI, I2C, and UART). ADC converts the output signal from the peak-hold circuit to digital information. DAC is used for adjustment of HV value at DC-HV converter on the R-Board. GPIO pins are connected with comparator output lines from R-Board and three LEDs on C-Board. These LEDs correspond to three scintillators and we can check the signals by eye in real time. SPI pins are connected with the DAC on R-Board for the adjustment of the comparator threshold. I2C and UART pins are connected to the pin headers/sockets as interfaces to commercial monitors such as thermometers, GPS, and so on. If the USB cable is connected between C-Board and PC, data taking and parameter setting can be done via serial communication. Wi-Fi and Bluetooth are also able to be used for network communication between the C-Board and PC. This network connection is currently in limited use and will be used in the future with code improvements. The peak-hold circuit is simply constructed with the low-cost fast op-amp (JRC NJU77701F) and transistor (TOSHIBA 2SC2712). The output signal from the amplifier circuit on R-Board is connected to the channel selector on C-Board, which selects one active channel out of three for deposit energy measurement. The selector is adopted due to the space limitation of the C-Board. The selected channel is connected to the peak-hold circuit. The held signal is sent to the ADC in the ESP32.

The R-Board and C-Board are connected by pin headers/sockets to form a two-stage structure, through which all signals and power supplies are transferred.

3. Current status of performance evaluation

Using the prototype of the OSECHI, we have tested the functions and evaluated the performance. As a first step, the hit rate and deposit energy measurements were performed. The OSECHI was located on the table in the laboratory at room temperature, and connected to the PC with a USB cable. The bias voltages of the SiPMs were set to the recommended operation voltages by HAMAMATSU. Threshold values were roughly set via the DAC control seeing the LED light by eye.

Figure 2 shows the count number of the hit events. Each colored line corresponds to each scintillator and black one shows the three coincidence events. In this result, the measured hit rate for each scintillator was to be 0.2 - 0.4 Hz. The coincidence rate was to be about 0.03 Hz. Figure 3 shows the obtained ADC distribution of the hit events. (a) is the ADC distribution of raw data. Using the coincidence information from comparator output, ADC distribution of events passing through the three scintillators is obtained, which is shown in (b). In the result, the shape of
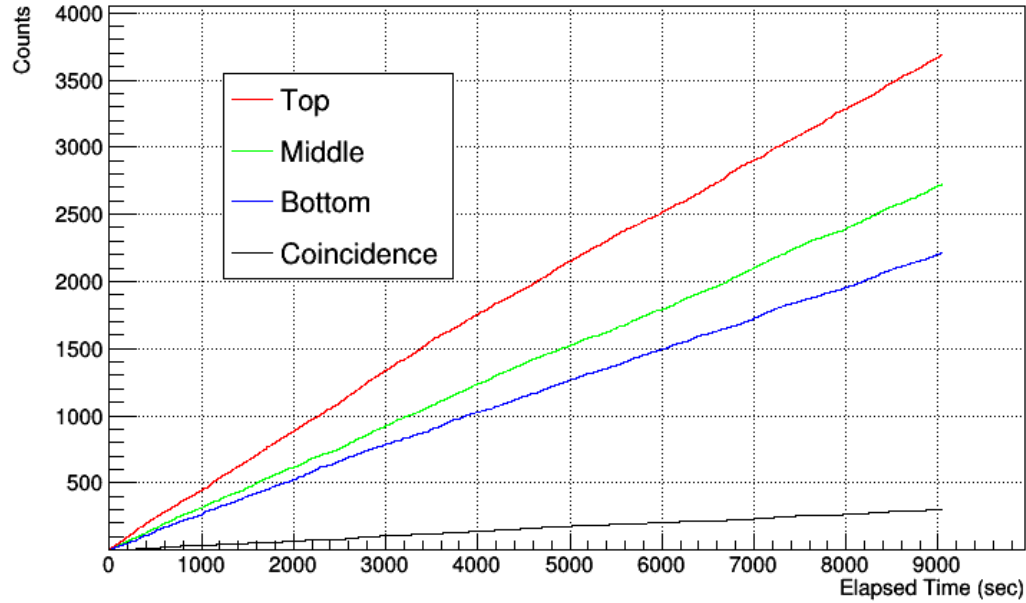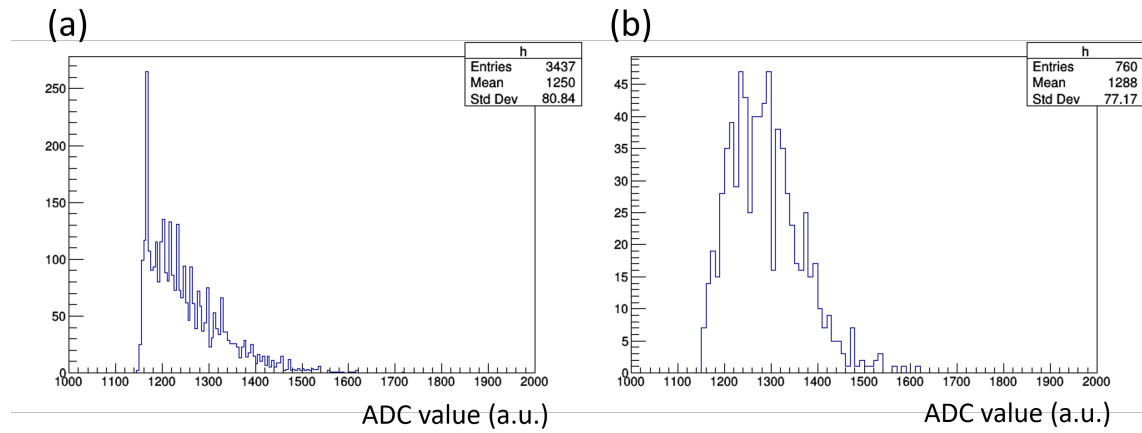
Figure 2: Rate measurement for cosmic muon with OSECHI. Red, Green, and Blue lines show the count numbers of the hit event with top, middle, and bottom scintillators, respectively. Black line shows the count number of three coincidence events.

Landau-like distribution can be seen in (b). A count rate measurement during a flight from Tokyo to Fukuoka was also performed using the OSECHI. Rough threshold adjustment was done just after the boarding, and the measurement started about 10 minutes after takeoff. Figure4 shows the result of the measurement. This figure shows that the event rate is increasing in the sky. From these results, it was found that the OSECHI can detect the cosmic muon.

However, some issues were also found. The measured rate was lower than expected, and the obtained shape of the ADC distribution was not clear. These are assumed to be due to reasons such as low light collection efficiency, coincidence conditions, and threshold adjustments. In addition, the gain of SiPM has a temperature dependency. Based on these, more investigation and improvements will be done. The scheme of the decision on the threshold and more improvements in the trigger and data acquisition system using ESP32 code are also needed.

4. Outreach and education

The development of the OSECHI was not completed yet, but some application uses were already performed. 10 or more OSECHIs were produced and those were used for the workshop in which the measurement of cosmic muon was done. In addition, in cooperation with a high school, a project, fun-Q, for muography of Japanese Kofun (ancient mounds) has been established and measurements are being made using OSECHI [7]. In the future, we can expect further expansion to include citizen science and others.

Figure 3: Measured ADC distribution for cosmic muon using OSECHI without coincidence (a) and with coincidence (b). In (b), the shape of Landau-like distribution can be seen.
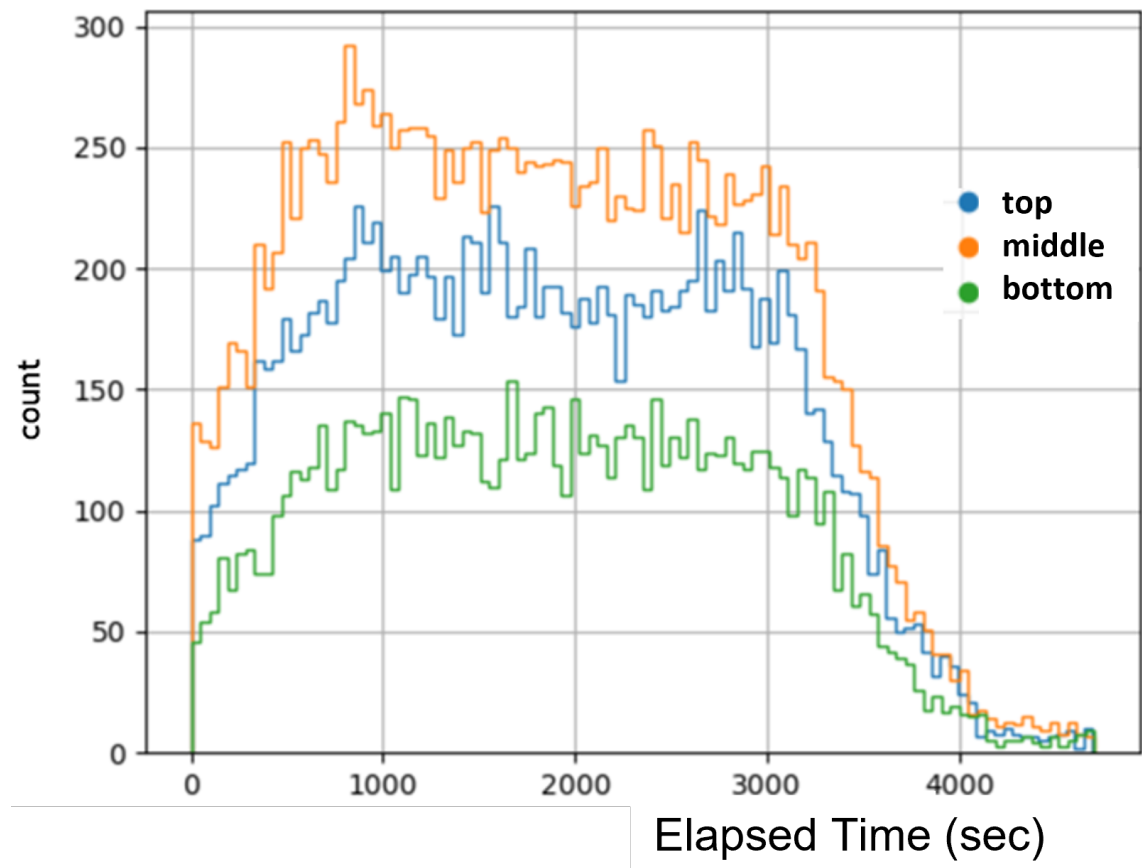
Figure 4: Count rate measurement during a flight from Tokyo to Fukuoka.

5. Summary

We developed a low-cost and compact detector, OSECHI, for citizen and student engagement in particle physics and astrophysics research. The entire detector is housed in a Japanese-style tiered bento box called "Jubako." OSECHI is capable of measuring cosmic-ray muons and consists of three scintillator layers that enable coincident event measurement. Silicon photomultipliers (SiPMs) are mounted on the scintillators for light collection. A custom-designed electronics board reads the SiPM output signals, recording charge and timing information. Real-time signal monitoring is facilitated by three LEDs corresponding to the scintillators. The board is USB-powered and includes a DC-HV converter for SiPM bias voltage. Signal processing functionalities are controlled by a chip microcontroller. Using a prototype of OSECHI, performance evaluation was performed and it was found that the OSECHI can measure the cosmic muon. However, some issues were also found. These will be investigated and more improvements will be promoted. In addition, the application uses of OSECHI for outreach and education are also performed, and further expansion to include citizen science and others are expected.

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