DESIGN OF NOVEL COMPACT DETECTOR BASED ON THE BISMUTH GERMANATE SCINTILLATOR AND SILICON PHOTOMULTIPLIER FOR ORTHO-POSITRONIUM PHYSICS*

HyeoungWoo Park[a], D.W. Jung[a], Sanghoon Hwang[b], H.J. Kim[a,†]

[a]Department of Physics, Kyungpook National University, Daegu 41566, Korea
[b]Korea Research Institute of Standards and Science, Daejeong, Korea

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Positronium decay research is one of the sensitive probes to discover new physical phenomena. Because of the pairing system of electron (particle) and positron (antiparticle), we can study reactions which are forbidden by the Standard Model. In this study, we designed a novel compact detector for precise measurement of ortho-positronium (o-Ps) decay. Due to their compact size, silicon photomultipliers (SiPMs) are used for the photodetection in the detector. The SiPM is well-known as a photodetector that can replace photomultiplier tube (PMT). In general, the size of the PMT is relatively large, so an SiPM was used to make compact trigger part for direct collection of scintillation light. In this research, the trigger part consists of plastic scintillator coupled directly to a single-channel SiPM to obtain the positron signal from the center of the detector. The trigger part is surrounded by the gamma-detection part to detect decay gammas in all directions. For dual readout, both sides of the Bismuth Germanate (BGO) scintillators are coupled with SiPMs. The designed frame and grid are used to support BGO scintillators and SiPMs. We obtained pretest data of a positron trigger signal and gamma-energy spectrum of ^{22}Na and ^{137}Cs radioactive sources for the novel compact detector. The detector will be used to study the C-parity violation, invisible, and rare decay search.

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1. Introduction

o-Ps is a purely leptonic system that is a bound state of a positron and an electron. The triplet spin state known as o-Ps has a relatively slow decay time of 142 ns with three-gamma annihilation [1]. Precise measurements of

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† Coresponding author: hongjoo@knu.ac.kr

o-Ps decay rate are not only important to study new physical phenomena, but also QED bound states, rare decay, C-violations and invisible decay can be studied [2]. Therefore, researchers take effort to develop a detector for the precise measurement of o-Ps [3, 4]. This precision measurement has been applied to many applications such as medical physics [5] and material analysis [6].

The reported positronium decay systems were composed of positron trigger and gamma-detection parts. Among them, for detectors designed with minimal dead area, the trigger part was typically coupled to a scintillation fiber and PMT [7]. The fiber trigger efficiency degrades due to significant scintillation light loss. Therefore, we designed a novel compact detector that directly collects scintillation light. The SiPM was used in the design, and its high gain ($\sim 10^6$), low operation voltage (< 100 V), and compact size make it particularly suitable for our trigger part design. This design is expected to achieve higher efficiencies than method where optical fibers were used as a trigger. Furthermore, the total detector size with gamma-detection parts is only 150 mm, allowing easy scale up and gamma detection. The detector design has also been modified based on the pretest results such as SiPM operating conditions optimization, inspection of each parts, gas environment, trigger positron tagging simulation, and o-Ps lifetime. The partial assembly results allow to verify possibilities of the novel compact detector for precise measurement of o-Ps.

2. Design of novel compact detector

The novel compact detector consist of the trigger and gamma-detection parts. The trigger part includes a plastic scintillator to measure the positron signal generated from β^+ decay. The gamma-detection part measures the annihilation photons from positronium. The trigger part is surrounded by the gamma-detection part to detect decay gammas in all directions.

2.1. The design of trigger

The trigger is designed with three main parts: positron generation, positron tagging, and o-Ps creation. The positron is produced from β^+ decay of a customized ^{22}Na radioactive sources made by the Korea Research Institute of Standards and Science (KRISS). The positron tagging part contains a 250 μm polyethylene naphthalate (PEN) film which is directly coupled with single-channel SiPM (SensL, MicroFJ-SMTPA-60036). The PEN film is a common commercialized product, and our preliminary experiment results showed similar performance to plastic scintillator (Eljen Technology, EJ-296). The upper layer of positron tagging part is covered with a 3M-VM2000 reflector to increase the collection of light. The porous material (silica aerogel) and the N_2 gas environment allow o-Ps creation and 3γ decay. Thus, the aerogel is placed in the N_2 gas environment. Figure 1 shows schematic of o-Ps detector and details of trigger concept.

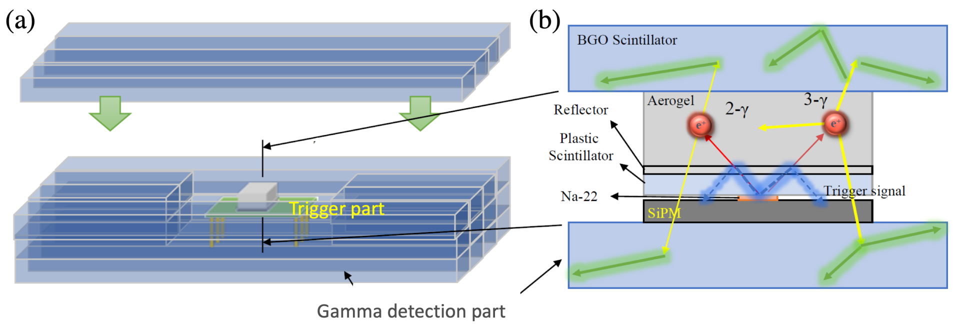

Fig. 1. Schematic diagram of (a) compact detector for o-Ps physics designed in such a way to minimize the dead area. (b) Trigger part which allows the direct detection of positron trigger signals with plastic scintillator and SiPM.

2.2. The design of gamma detector

The gamma detector consists of a Bismuth Germanate (BGO, $Bi_4Ge_3O_{12}$) scintillator. The BGO scintillator is a very efficient gamma absorber because of its high effective atomic number and high density. The good optical quality BGO scintillator that was provided by the Nikolaev Institute of Inorganic Chemistry (NIIC) in Russia is coupled with a four-channel SiPM (SensL, ArrayJ-60035-4P-EVB) for the gamma detection. For dual readout, both sides of the BGO scintaillators are coupled with 7×7 arrangement of 2×2 arrays for a total of 14×14 SiPMs. The BGO scintillator layout used in the detector is an array of 14×14, which is 192 BGO scintillators ($7.5 \times 7.5 \times 150$ mm^3) placed except an array of 2×2 for trigger part space. The array of 2×2 is filled with BGO scintillators ($7.5 \times 7.5 \times 50$ mm^3) in the form of endcaps to detect decay gamma in all directions.

2.3. Data acquisition system

The detector signal requires several steps to make it a signal that can be analyzed. First of all, each preamplifier is directly attached to the output of SiPM to minimize signal loss. The signal is processed by the peak sum width (PSW) method at 65 MHz flash analog-to-digital converter (FADC). All data are gathered by the trigger control board (TCB) and sent to the computer with time information at 2 ns resolution. Data are taken with ROOT [8] based DAQ system and stored with ROOT-supported format. The electronics system is developed with NOTICE Co. [9].

3. Results and discussion

3.1. Operating conditions optimizations of SiPM

For the dual readout scintillation light from about 200 BGO scintillators, 400 SiPM channels (100 4-channel SiPMs) are required. The performance of each SiPM was analyzed by measuring the energy spectrum from BGO scintillator under the excitation of 662 keV from a ^{137}Cs radioactive source. Figure 2 (a), (b) shows the variation of SiPM (Coupled with BGO) light output and energy resolution at 661 keV. The optimization of the operating conditions for SiPM is necessary because of the gain and noise variation depending on the operating voltage. Figure 2 (c) shows that the optimized operating voltage is 28 V.

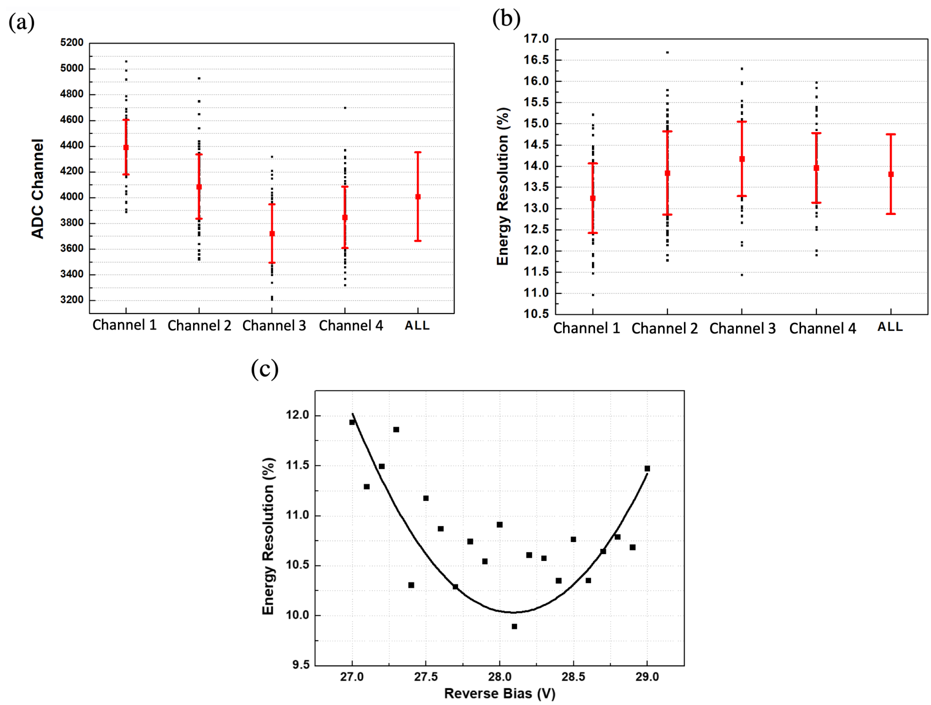

Fig. 2. (a) Light collection and (b) energy resolution measurement results to confirm the characteristic variation of SiPMs in each of the 400 channels. (c) Optimization of SiPM bias voltage.

3.2. Trigger of positron tagging

Triggering through positron tagging is one of the most important parts of this detector. As shown in Fig. 3, the positron trigger signal is well-acquired due to the reflection structure and efficient light collection by direct light sensor coupling. The energy spectra of the positrons also show good agreement with Geant4 [10] Monte Carlo simulation results.

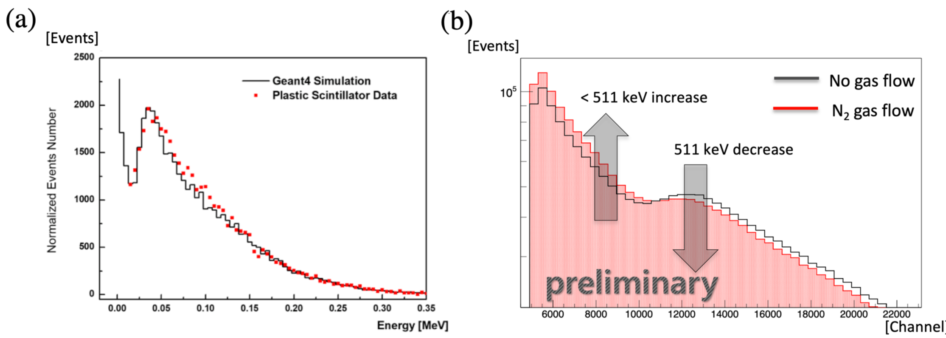

Fig. 3. (a) Comparison of positron trigger signals from detectors and simulation results. (b) Energy distribution of gamma decays obtained with the partial assembly. The arrows indicate the change in energy distribution due to atmospheric and nitrogen ambient conditions.

3.3. o-Ps lifetime measurement

o-Ps lifetime is 142 ns in vacuum but it has a relatively short lifetime in normal environments. Especially, the pick-off quenching process makes o-Ps decay to 2γ instead of 3γ decay. If o-Ps undergoes a 2γ decay, it is not possible to study the desired phenomenon, so it is necessary to create an environment in which 3γ decay can occur. o-Ps can decay into 3γ in N_2 gas environment and have a nearly vacuum-like lifetime.

3.4. Partial assembly results

Partial assembly of the detector consists of 56 BGO crystals dually coupled to SiPMs. The signal was acquired on about 112 channels of SiPM. The data was obtained on atmospheric and nitrogen ambient conditions, respectively. The presence of the 3γ decay of o-Ps resulted in different ratios of the energy regions lower and higher than 511 keV as shown in Fig. 3 (b).

4. Summary

The compact SiPM-based detector with BGO crystals for o-Ps physics is designed. The partial assembly measurement results confirmed the feasibility of studying new physics with the detector. Especially, the basic characteristics of each part were investigated and optimized for the detector design. The new structure of the light collection on the trigger part increased the trigger efficiency. The lifetime measurements of o-Ps under different gas conditions show the possibility of conducting experiment with this detector. It is expected that the novel compact detector can be used to search for C-parity violation as well as invisible and rare o-Ps decays.

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