Nuclear Instruments and Methods in Physics Research A 851 (2017) 118–124

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

NaI(Tl) scintillator read out with SiPM array for gamma spectrometer

Tuchen Huang, Qibin Fu, Shaopeng Lin, Biao Wang*

Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-sen University, Zhuhai 519082, China

A R T I C L E I N F O

Keywords:
Gamma spectrometry
SiPM
NaI(Tl)
Energy resolution

A B S T R A C T

The NaI(Tl) scintillator is widely used in gamma spectrometer with photomultiplier tube (PMT) readout. Recently developed silicon photomultiplier (SiPM) offers gain and efficiency similar to those of PMT, but with merits such as low bias voltage, compact volume, low cost, high ruggedness and magnetic resonance compatibility. In this study, 2-in. and 1-in. NaI(Tl) scintillators were readout with SiPM arrays, which were made by tiling multiple SiPMs each with an active area of 6×6 mm^2 on a printed circuit board. The energy resolutions for 661.6 keV gamma rays, obtained with Φ2×2 in. scintillator coupled to 6×6 ch SiPM array and Φ1×1 in. scintillator coupled to 4×4 ch SiPM array were 7.6% and 7.8%, respectively, and were very close to the results obtained with traditional bialkali PMT (7.3% and 7.6%, respectively). Scintillator coupled to photodetector with smaller area was also studied by adding a light guide or using scintillator with tapered head. The latter showed better performance than using light guide. The 1-in. NaI(Tl) scintillator with tapered head coupled to 2×2 ch SiPM array achieved 7.7% energy resolution at 661.6 keV, the same as that obtained with standard Φ1×1 in. scintillator coupled to 4×4 ch SiPM array. While the 2-in. scintillator with similar geometry showed degraded energy resolution, 10.2% at 661.6 keV, but could still be used when high efficiency is preferred over energy resolution.

1. Introduction

Scintillation detectors, mainly inorganic scintillators, are the most widely used detectors in gamma spectrometers because of low cost and availability in large size. The thallium-doped sodium iodide [NaI(Tl)] scintillator is the most commonly used inorganic scintillator because of its high light yield, high density, low cost and mature manufacturing technique. Photomultiplier tubes (PMTs) are commonly used for NaI(Tl) scintillators, but they have disadvantages such as bulky, fragile, high operating voltage, sensitivity to magnetic field and complex manufacturing.

In recent years, a novel semiconductor photodetector called silicon photomultiplier (SiPM) has been developed. A single SiPM consists of several thousand or more small microcells connected in parallel. Each microcell consists of an avalanche photodiode (APD) operating in Geiger mode and a quenching resistor in series. The summed output signal is proportional to the total number of microcells that are triggered by the absorption of photon. A prominent feature of SiPM is the high gain at the level of 10^6 which makes it an alternative to PMT. SiPMs have advantages over PMTs such as low bias voltage, high ruggedness, insensitivity to magnetic fields, and mass production.

The performances of different kinds of scintillators coupled to SiPM were studied detailedly in Ref. [1–4], and results showed that energy resolution obtained with SiPM was close to that obtained with PMT (even better for some scintillators) when using small scintillator (3–6 mm) coupled to matched SiPM. But detection efficiency is very low for such small scintillator which is unpractical for gamma spectrometer. Fortunately, the compact package of SiPM makes it feasible to build an array to matched large scintillator.

As reported in Ref. [5,6], 4×4 ch and 8×8 ch SiPM arrays (3×3 mm^2 active area per channel) were used for 1-in. and 2-in. NaI(Tl) scintillators. In Ref. [7], 2-in. NaI(Tl) scintillator was coupled to a 4×4 ch SiPM array (3×3 mm^2 active area per channel) using light guide. The SiPM arrays used in Ref. [5,7] are commercial monolithic arrays, which are old designs and already out of production. The SiPM arrays (S12642 series) used in Ref. [6] are also ready-made products from Hamamatsu using the TSV (Through Silicon Via) technology. The adoption of TSV structure makes it possible to eliminate wiring on the photosensitive area side, resulting in a compact structure with little dead space (only 0.2 mm gap between adjacent channels). The newest product from Hamamatsu using TSV technology is the S13361 series, with total active area only up to 24×24 mm^2 [8].

In this work, SiPM arrays were built by tiling multiple standard SiPMs on a printed circuit board (PCB). Arrays with arbitrary number of channels can be made. SiPMs with an active area of 6×6 mm^2 are used, which is the largest size of currently available. Standard Φ1×1 in.

* Corresponding author.
E-mail address: wangbiao@mail.sysu.edu.cn (B. Wang).

http://dx.doi.org/10.1016/j.nima.2017.01.068
Received 19 September 2016; Received in revised form 11 January 2017; Accepted 27 January 2017
Available online 31 January 2017
0168-9002/

Table 1
Main parameters of the used SiPM and fabricated arrays.

Manufacturer	SensL		
Model	MicroFC−60035		
Active area	6×6 mm^2		
Package dimension	7×7 mm^2		
Number of APD-cells	18,980		
APD-cell size	35×35 μm		
Microcell fill factor	64%		
Rated gain	3×10^6		
Spectral range	320–900 nm		
Maximum sensitivity	420 nm		
Capacitance	3400 pF		
Fabricated array	2×2 ch	4×4 ch	6×6 ch
Number of channels	4	16	36
Total active area (mm)	12×12	24×24	36×36
Total number of APD cells	75,920	303,680	683,280

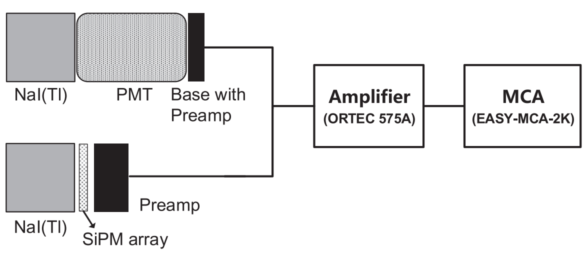

Fig. 1. Experiment setup for gamma spectrum measurements.

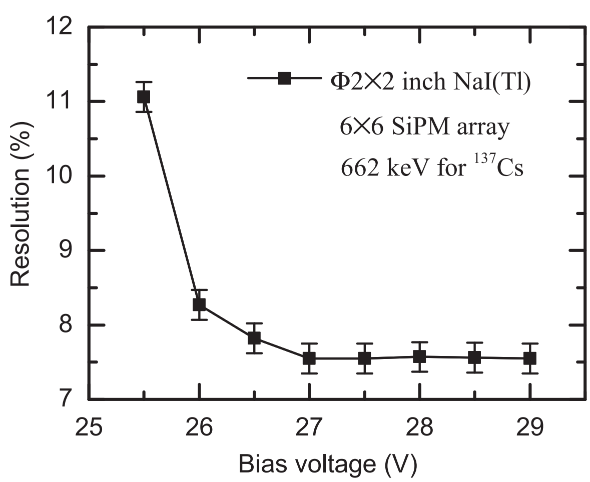

Fig. 2. Energy resolution of 661.6 keV gamma-rays versus bias voltage for the Φ2×2 in. NaI(Tl) scintillator coupled to 6×6 ch SiPM array.

and Φ2×2 in. NaI(Tl) scintillators were read out with 4×4 ch and 6×6 ch arrays, respectively, with comparison to PMT. For coupling large scintillator to small photodetector, light guides with different reflector and length were tested. According to the experiment results with light guides, an alternative approach was developed using scintillator with tapered head. The performances of both 2-in. and 1-in. scintillators with tapered head coupled to simple 2×2 ch SiPM array were evaluated.

2. Energy resolution of scintillation detector

The energy resolution of the full energy peak measured with scintillation detector can be expressed as [5]:

$$\left(\frac{\Delta E}{E}\right)^2 = (\delta_{sc})^2 + (\delta_p)^2 + (\delta_{st})^2 + (\delta_n)^2 \tag{1}$$

where δ_{sc} is the intrinsic resolution of the crystal, δ_p is the transfer resolution, δ_{st} is the statistical contribution of the photodetector and δ_n is the dark noise contribution connected with the detector's current and the noise of the electronics. The statistical uncertainty of the signal from the photodetector can be described as [5]:

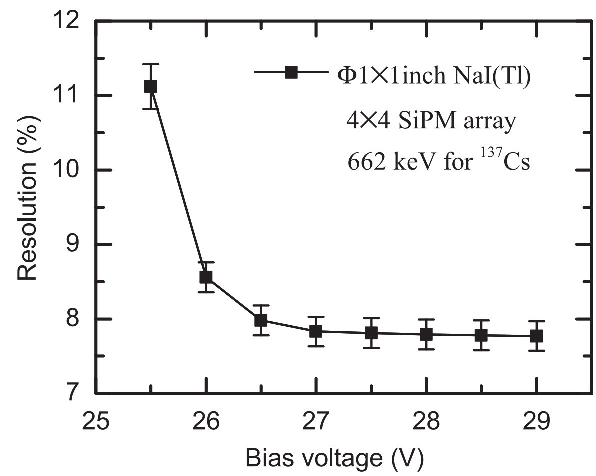

Fig. 3. Energy resolution of 661.6 keV gamma-rays versus bias voltage for the Φ1×1 in. NaI(Tl) scintillator coupled to 4×4 ch SiPM array.

$$\delta_{st} = 2.355 \times (ENF/PHE)^{1/2} \tag{2}$$

where PHE is the number of photoelectrons and ENF is the excess noise factor.

ENF for PMTs comes from variance of the electron multiplier gain and has a value of 1.1–1.2 for modern PMTs. For SiPMs, ENF is caused by crosstalk and afterpulses. PHE is proportional to the Photon Detection Efficiency (PDE). Both PDE and probability of crosstalk and afterpulses will increase with bias voltage. Thus optimum bias voltage should be determined to achieve the best energy resolution.

The number of photoelectrons (phe) was measured using pulse height resolution (PHR) method [1]. The PHR method (PHE_{phr}) is based on the calculation of the photoelectron's number from the pulse height resolution of a LED light pulse peak assuming a Gaussian curve and an ENF value of 1. A blue LED with peak wavelength at 428 nm was used, and the pulse width was set to 250 ns according to the decay time of NaI(Tl) scintillator. For uniform illumination, the LED was placed at certain distance from the SiPMs, with light attenuator and diffuser inserted in between. Besides, diffuse reflector (white paper) was added around the SiPMs. The peak position of LED pulse corresponds to the given energy of gamma rays. Assuming the ENF equal to 1, the calculated phe number using PHR method represents the lower limit of the phe number [5].

$$PHE_{phr} = (2.355/\delta_{st})^2 \tag{3}$$

The number of photoelectrons per unit energy (phe/MeV) was measured using PHR method (PHE_{phr}) for tested scintillators illuminated with the ^{137}Cs gamma source.

3. Scintillator read out with SiPM array

The SiPMs used in this work are standard products from SensL Technologies Ltd. The main parameters of the SiPM and fabricated arrays are collected in Table 1. Standard Φ2×2 in. and Φ1×1 in. NaI(Tl) scintillators from Beijing Hamamatsu Photon Techniques Inc were used. A 2-in. head-on bialkali PMT (Model CR105) was used for comparison. Silicone oil was used for optical coupling between the components. The experiment setup based on NIM system is shown in Fig. 1. Shaping time of 1.5 μs was chosen for the amplifier. All the tests were carried out in an air-conditioned laboratory, at temperature of 24 °C.

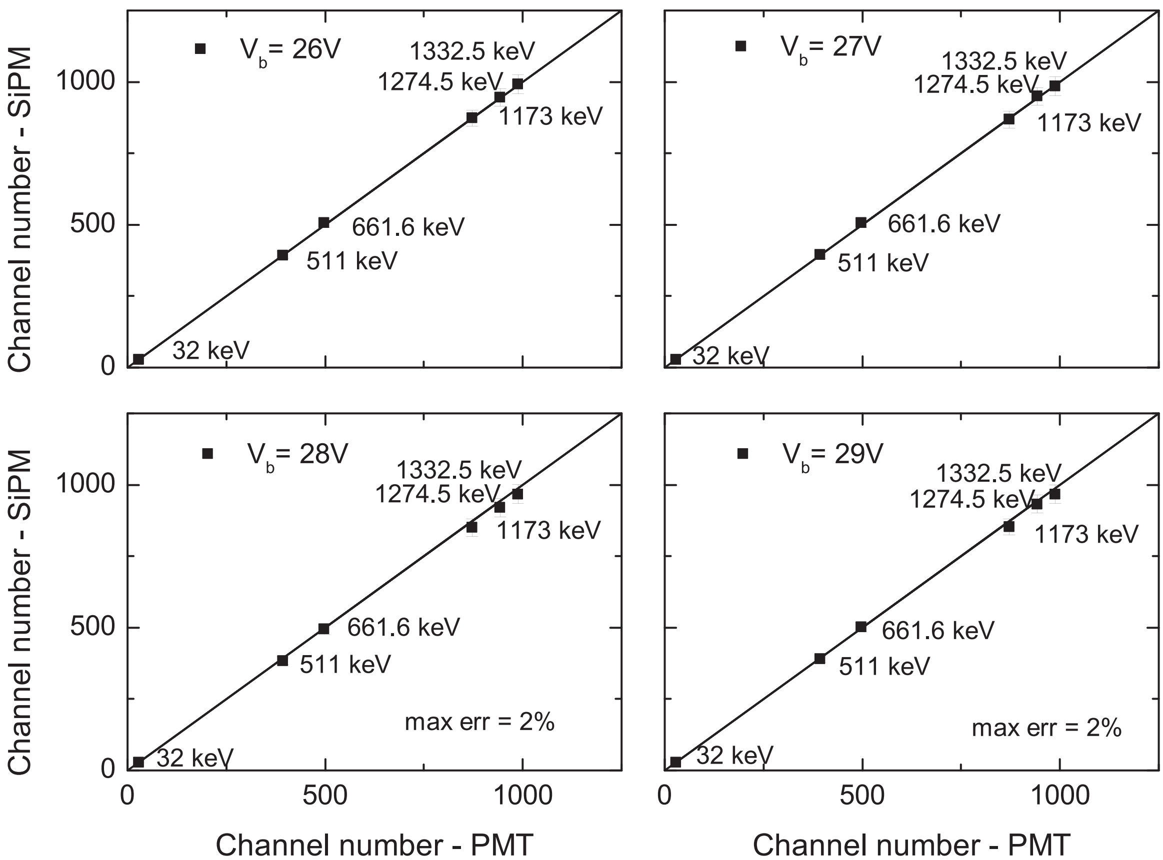

Fig. 4. Linearity for the Φ2×2 in. NaI(Tl) scintillator coupled to 6×6 ch SiPM array at different bias voltages.

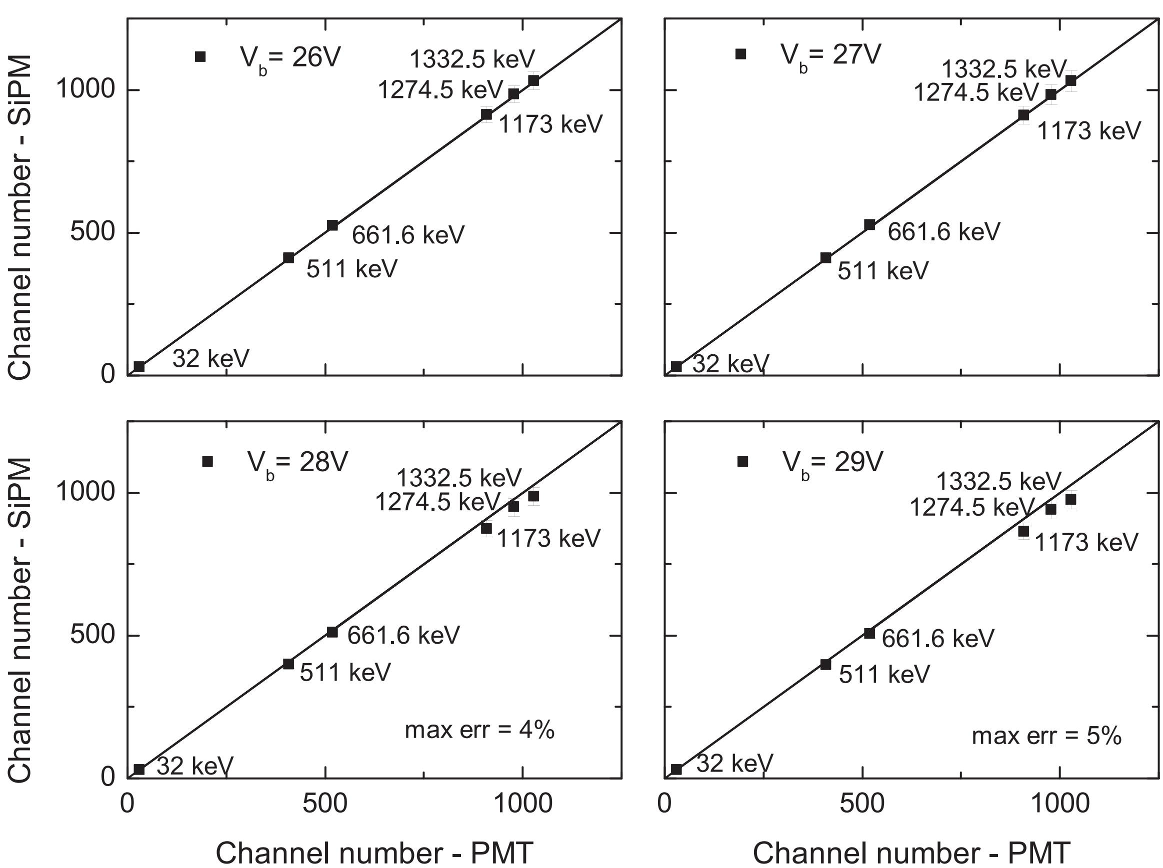

Fig. 5. Linearity for the Φ1×1 in. NaI(Tl) scintillator coupled to 4×4 ch SiPM array at different bias voltages.

Table 2
Energy resolution for NaI(Tl) scintillator coupled to PMT and SiPM array.

scintillator	photodetector	energy resolution (%) at peaks (keV)					phe/MeV
		511	661.6	1173	1274.5	1332.5	
Φ2 × 2 inch	PMT	8.2 ± 0.3	7.3 ± 0.2	5.5 ± 0.3	5.9 ± 0.2	5.4 ± 0.3	5740 ± 170
Φ2×2 in.	6×6 SiPM array (36×36 mm^2)	8.6 ± 0.3	7.6 ± 0.3	5.9 ± 0.3	6.0 ± 0.3	5.5 ± 0.3	4840 ± 240
Φ2×2 in.	4×4 SiPM array (24×24 mm^2)	9.6 ± 0.4	8.1 ± 0.3	6.8 ± 0.3	6.4 ± 0.2	6.0 ± 0.4	3200 ± 160
Φ1×1 in.	PMT	8.4 ± 0.3	7.6 ± 0.2	5.2 ± 0.3	5.9 ± 0.3	5.3 ± 0.3	5980 ± 160
Φ1×1 in.	4×4 SiPM array (24×24 mm^2)	8.6 ± 0.3	7.8 ± 0.3	5.3 ± 0.3	6.0 ± 0.2	5.3 ± 0.4	5670 ± 350

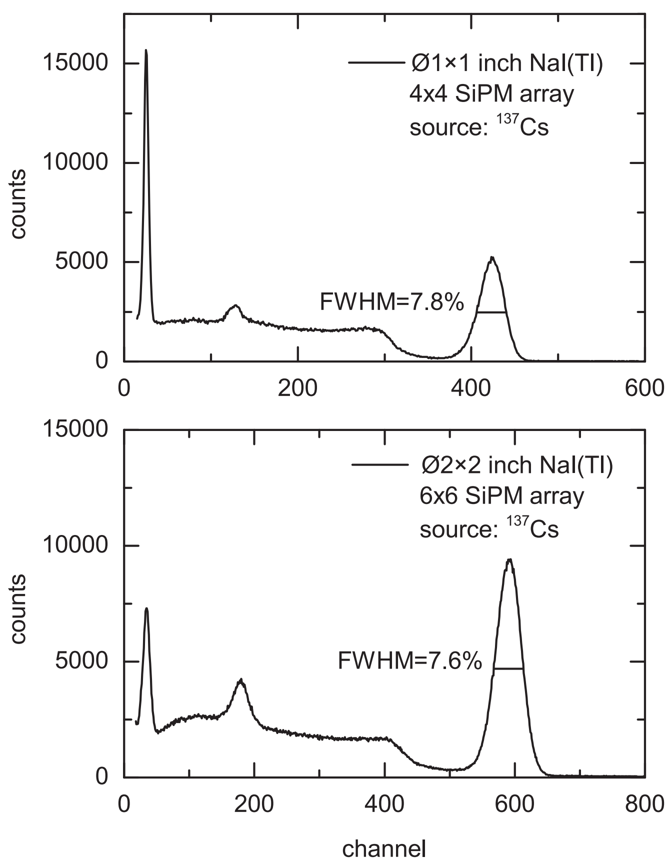

Fig. 6. The energy spectra of 661.6 keV gamma rays, as measured with the Φ1×1 in. and Φ2×2 in. NaI(Tl) scintillators coupled to SiPM array.

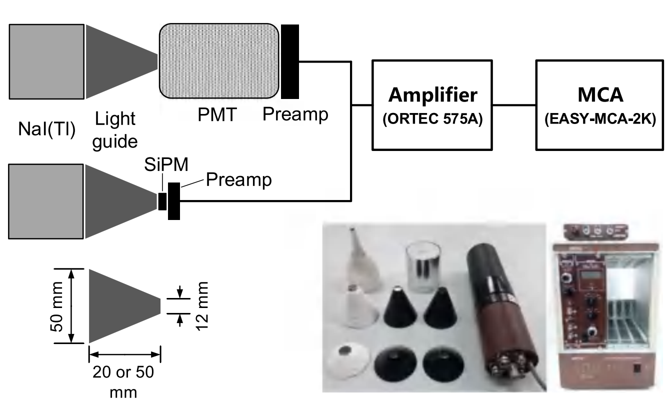

Fig. 7. System setup with light guide and related components.

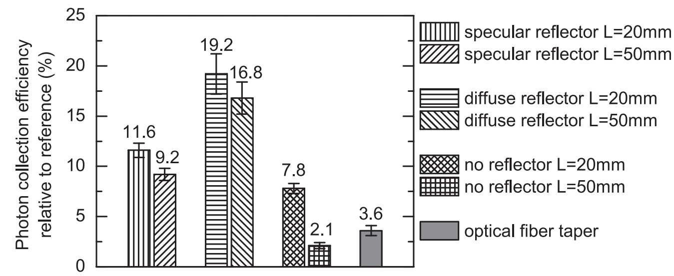

Fig. 8. Photon collection efficiency for different light guides with PMT.

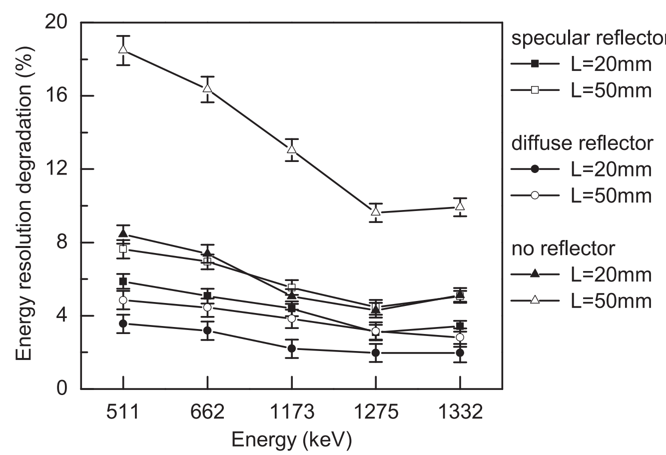

Fig. 9. Degradation of energy resolution for different light guides with PMT compared to the reference system.

To determine the optimum bias voltage for SiPM array, energy resolution for 661.6 keV gamma rays was measured at different bias voltages and the results are shown in Figs. 2 and 3. Energy resolution improved as bias voltage increased when the voltage was low, but reached a constant value for bias voltage higher than 27 V.

The linearity was checked using the method as described in Ref. [5]. Three spectra with ^{22}Na (511, 1274.5 keV), ^{137}Cs (32, 661.6 keV) and ^{60}Co (1173, 1332.5 keV) gamma sources were measured and the positions of the full energy peaks were determined, which were then compared to the measurements with PMT. Peak position of the 32 keV X-ray from ^{137}Cs was used for normalization of the PMT response to the SiPM response. The response of the Φ2×2 in. scintillator coupled to 6×6 ch SiPM array and Φ1×1 in. scintillator coupled to 4×4 ch SiPM array are shown in Figs. 4 and 5 respectively. Solid line is a theoretical line which represents the ideal case, where the SiPM response is fully proportional to the PMT response. At bias voltage 26 V and 27 V, the SiPM responses were well linear in the energy range up to 1332.5 keV

Table 3
Energy resolution with light guide and SiPM array.

scintillator	light guide	photodetector	energy resolution (%) at peaks (keV)				
			511	661.6	1173	1274.5	1332.5
Φ2× 2 in.	None	PMT	8.2 ± 0.3	7.3 ± 0.2	5.5 ± 0.3	5.9 ± 0.2	5.4 ± 0.3
Φ2 × 2 inch	L=20 mm PTFE wrapping	PMT	11.8 ± 0.6	10.5 ± 0.6	7.7 ± 0.5	7.9 ± 0.5	7.3 ± 0.5
Φ2 × 2 inch	L=20 mm PTFE wrapping	2×2 SiPM array (12 × 12 mm^2)	13.2 ± 0.7	11.7 ± 0.7	8.5 ± 0.6	8.6 ± 0.6	8.0 ± 0.6
Experiment results from Ref. [7]							
Φ2 × 2 inch	None	PMT	8.37	7.31	7.26	5.62	6.56
Φ2 × 2 inch	L=17 mm PTFE coating	4×4 SiPM array (12 × 12 mm^2)	16.64	14.11	NA	10.35	NA

for both settings. As bias voltage increased, nonlinear responses were observed. The maximum deviation was 2% for the Φ2×2 in. scintillator coupled to 6×6 ch SiPM array at bias voltage of 29 V, while this value was 5% for the Φ1×1 in. scintillator coupled to 4×4 ch SiPM array. In the following experiment, bias voltage was set to 27 V for the 4×4 ch and 6×6 ch SiPM arrays, corresponding to an overvoltage of 2.5 V.

Experiment results for the NaI(Tl) scintillators coupled to PMT and SiPM arrays are summarized in Table 2. For the Φ2×2 in. scintillator coupled to 6×6 ch SiPM array and Φ1×1 in. scintillator coupled to 4×4 ch SiPM array, measured energy resolutions are very close to that obtained with PMT. For the Φ2×2 in. scintillator, the 4×4 ch SiPM array showed slightly worse performance than the 6×6 ch SiPM array. Similar experiment were reported in Ref. [6] with Φ2×2 in. and Φ1×1 in. NaI(Tl) scintillators readout by 8×8 ch SiPM array (3×3 mm^2 active area per channel), and the energy resolution for the 661.6 keV peak were 7.92% and 6.79%, respectively, while the values were 6.62% and 6.39% using XP5500B PMT.

The energy spectra of gamma rays from ^{137}Cs source measured with the Φ1×1 in. and Φ2×2 in. NaI(Tl) scintillators coupled to SiPM array are shown in Fig. 6. Backscattering peak was clearly observed because the system was put in a metal box for light and electromagnetic shielding.

4. Scintillator coupled with light guide

For coupling large scintillator to small photodetector, the Φ2×2 in. NaI(Tl) scintillator was tested with light guides. The experiment setup was similar to that described in Ref. [7]. The light guides were fabricated using optical glass in the shape of truncated cone. The diameter of incident surface was 50 mm while diameter of exit surface was 12 mm. Different reflectors were tested including: 1) aluminium coating as specular reflector; 2) teflon sheet wrapping as diffuse reflector; 3) bare light guides with no reflector for comparison. Light guides with two different lengths (20 mm and 50 mm) were compared for each configuration. For the aluminium coated and bare light guides, side surface was covered with black sheet for light shielding. An off-the-shelf optical fiber taper was also tested, which was commonly used for coupling image to CCD detector. Fig. 7 shows the system setup with light guide and related components.

For the system with light guide, the number of photons collected by the photodetector will be reduced compared to direct coupling system. The loss of photons degrades the energy resolution by decreasing the number of photoelectrons PHE in Eq. (2). Also, the introduction of light guide affects the transfer resolution δ_p. The light collection efficiency varies with the position of gamma reaction in a scintillator and light guide will change this dependency. As described in Ref. [7], light guide makes light collection efficiency more uniform, which has a positive effect on energy resolution.

The performance of light guide was evaluated with PMT (the same one as used in Section 3) readout for easy assemble. Fig. 8 shows the relative photon collection efficiency compared to the reference system (Φ2×2 in. scintillator coupled to PMT directly as in Fig. 1). Less than 20% of the photons were collected using light guides. The light guides with diffuse reflector showed higher efficiency than the light guides with specular reflector. Photon collection efficiency decreased as the length of light guide increased, which was particularly evident for the light guides without reflector. The optical fiber taper usually has better light transmission efficiency than traditional light guide, but the result was very poor in this experiment. The reason was believed to be the drop of transmission efficiency below 500 nm and non-Lambertian light source.

The degradation of energy resolution for different light guides compared to the reference system is shown in Fig. 9. The light guide with diffuse reflector and 20 mm length showed the best performance corresponding to 2–4% degradation of energy resolution for all the peaks. As the length of light guide increased, the energy resolution degradation only changed slightly for light guides with diffuse reflector, while the change was more obvious for light guides with specular reflector.

The experiment results for the best light guide (light guide with diffuse reflector and 20 mm length) coupled to PMT and 2×2 ch SiPM array are shown in Table 3. Energy resolution obtained with SiPM array is slightly worse than that obtained with PMT. Energy resolution of the 661.6 keV peak is equal to 11.7%, better than the obtained result in Ref. [7] with similar setup.

5. Scintillator with tapered head

According to the experiment results with light guides, an alternative configuration was developed using scintillator with tapered head, as shown in Fig. 10. The tapered section plays the same role as the light guide eliminating an extra component. This is expected to have better performance than light guide by reducing one optical coupling face. For the 2-in. scintillator, the length of tapered section was set to 20 mm, the same as the length of the best light guide in Section 4. An 1-in. scintillator with similar structure was also made. These two scintillators were readout with PMT and 2×2 ch SiPM array (12 × 12 mm^2 active area).

Table 4 summarizes the experiment results for scintillators with tapered head. Systems with SiPM readout have nearly the same performance compared to the same scintillator with PMT readout. For the 2-in. scintillator with tapered head coupled to SiPM array, energy resolution of 10.2% was measured for the 661.6 keV peak, which is better than the result with light guide (11.7%), and light collection was improved relatively by 20%. The 1-in. scintillator with tapered head shows almost the same performance as standard Φ1 × 1 inch scintillator readout with PMT, although only 50% light was collected relatively. The use of light guide makes light collection efficiency more uniform, which has a positive effect on energy resolution [7], and this is believed to hold true for scintillator with tapered

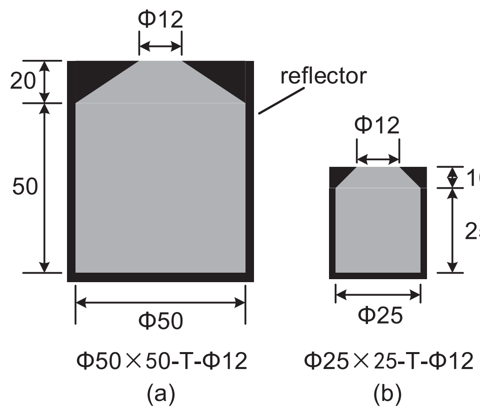

Fig. 10. Schematics of the scintillators with tapered head.

head. The structure of scintillator with tapered head can be further optimized with light transport simulation software as described in Ref. [9].

The energy spectra of gamma rays from ^{137}Cs source measured with scintillators with tapered head coupled to 2×2 ch SiPM array are shown in Fig. 11. Backscattering peak was clearly observed because the system was put in a metal box for light and electromagnetic shielding.

6. Summary

The performances of 2-in. and 1-in. NaI(Tl) scintillators readout with SiPM arrays for gamma spectrometer were evaluated. SiPM arrays were built by tiling multiple SiPMs ($6 \times 6\ \text{mm}^2$ active area for each) on a printed circuit board. Optimum bias voltage was selected base on the results of measured energy resolution versus bias voltage. Energy resolutions measured with the $\Phi 2 \times 2$ and $\Phi 1 \times 1$ inch scintillators coupled to 6×6 ch and 4×4 ch SiPM arrays respectively were 7.6% and 7.8%, which were very close to that measured with PMT. Good linearity was obtained in energy range up to 1332.5 keV.

Table 4
Energy resolution for scintillators with tapered head.

Scintillator	Photodetector	Energy resolution (%) at peaks (keV)					phe/MeV
		511	661.6	1173	1274.5	1332.5	
Φ50×50-T-Φ12	PMT	10.9 ± 0.3	9.7 ± 0.3	7.0 ± 0.3	7.2 ± 0.3	6.7 ± 0.2	1320 ± 40
Φ50×50-T-Φ12	SiPM array	11.5 ± 0.4	10.2 ± 0.3	7.4 ± 0.3	7.5 ± 0.3	7.0 ± 0.3	1260 ± 70
Φ25×25-T-Φ12	PMT	8.5 ± 0.3	7.6 ± 0.3	5.1 ± 0.2	5.6 ± 0.3	5.1 ± 0.2	2990 ± 90
Φ25×25-T-Φ12	SiPM array	8.6 ± 0.3	7.7 ± 0.3	5.1 ± 0.3	5.7 ± 0.3	5.3 ± 0.3	2840 ± 140

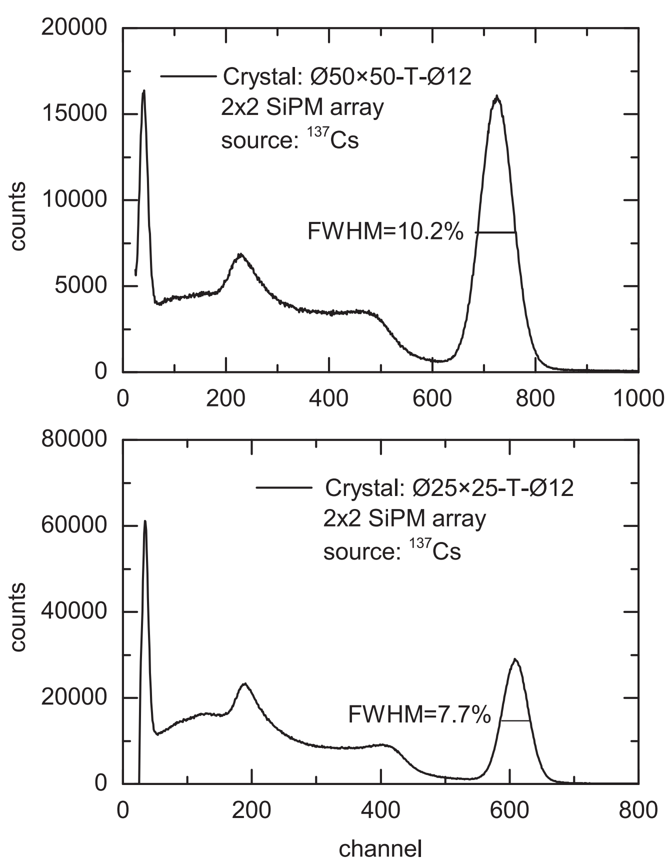

Fig. 11. The energy spectra of 661.6 keV gamma rays for the scintillators with tapered head coupled to 2×2 SiPM array.

For simplicity, the 2-in. scintillator was coupled to photodetector with smaller area by use of light guide. Light guides with different reflector and length were made and their performances were evaluated. Light guides with diffuse reflector showed better performance than light guides with specular reflector. As the length of light guide increased, the photon collection efficiency decreased and energy resolution deteriorated. The best system with light guide readout by 2×2 ch SiPM array achieved 11.7% energy resolution at 661.6 keV.

Scintillators with tapered head were developed as an alternative structure to light guide. This scheme showed better resolution than using light guide. The 1-in. NaI(Tl) scintillator with tapered head coupled to 2×2 ch SiPM array achieved 7.7% energy resolution at 661.6 keV, the same as that obtained with $\Phi 1 \times 1$ inch scintillator coupled to 4×4 ch SiPM array. While the 2-in. scintillator with similar geometry showed degraded energy resolution, 10.2% at 661.6 keV, but could still be used when high efficiency is required and energy resolution is not so critical.

The combination of NaI(Tl) scintillator and SiPM array could be an ideal solution for compact gamma spectrometer, such as the Spectroscopic Personal Radiation Detectors (SPRDs). The volume and weight can be significantly reduced using SiPM and no high voltage requirement also brings in great advantage on power consumption. Also the ruggedness is improved, which is very important for hand-held devices.

Better performance can be expected using SiPMs with improved characteristics, mainly higher PDE and lower dark noise. The new TSV packaging technology can reduced the dead space significantly when building an array. Also, the PDE and dark noise of SiPMs are continuously improving. It's believed that SiPM will replace PMT in more and more applications.

References

[1] M. Grodzicka, et al., Energy resolution of small scintillation detectors with SiPM light readout, J. Instrum. 8 (2013) 2017.

[2] M. Grodzicka, et al., MPPC array in the readout of CsI, LSO, LaBr and BGO scintillators, IEEE Trans. Nucl. Sci. 59 (2012) 3294.

[3] T. Szczesniak, et al., Characteristics of scintillation detectors based on inorganic scintillators and SiPM light readout, Nucl. Instrum. Methods Phys. Res. Sect. A 702 (2013) 91.

[4] P.F. Bloser, et al., Testing and simulation of silicon photomultiplier readouts for scintillators in high-energy astronomy and solar physics, Nucl. Instrum. Methods Phys. Res. Sect. A 763 (2014) 26.

[5] M. Grodzicka, et al., Characterization of 4×4 ch MPPC array in scintillation spectrometry, J. Instrum. 8 (2013) 09020.

[6] M. Grodzicka, et al., Characterization of TSV MPPC arrays (4×4 ch and 8×8 ch) in scintillation spectrometry, IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2014 IEEE.

[7] C. Kim, et al., Replacement of a photomultiplier tube in a 2-inch thallium-doped sodium iodide gamma spectrometer with silicon photomultipliers and a light guide, Nucl. Eng. Technol. 47 (2015) 479.

[8] Hamamatsu, S13361 Series MPPC Array, ⟨http://www.hamamatsu.com/us/en/product/category/3100/4004/4114/index.html⟩.

[9] H. Yoo, et al., Optimal design of a CsI(Tl) crystal in a SiPM based compact radiation sensor, Radiat. Meas. 82 (2015) 102.