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Abstract

NaI(Tl) crystal is a common radiation detector material. Since its interaction with radiation produces weak optical signals, a photomultiplier tube is required to convert the optical signals into electrical signals for processing by subsequent circuits. Silicon photomultiplier (SiPM), as a novel photoelectric conversion device, offers advantages of low noise, small size, low power consumption, and magnetic field immunity compared to traditional photomultiplier tubes. Therefore, NaI(Tl) scintillation detectors designed with SiPM feature compact size, high efficiency, high sensitivity, and strong interference immunity; through optimization of the detector's physical structure and signal processing circuit, efficient detection of gamma rays is achieved. This paper presents the design and development of a 1-inch NaI(Tl) detector employing SiPM, which features compact size and low background noise. The energy spectrum response of the detector to a 137Cs source was tested, and the results demonstrate that the detector achieves an energy resolution of 8.72% for 0.662 MeV gamma rays.

Full Text

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Abstract

NaI(Tl) crystal is a common radiation detector material. Since its interaction with radiation produces weak optical signals, photomultiplier tubes have traditionally been required to convert these optical signals into electrical signals for subsequent circuit processing. Silicon photomultipliers (SiPMs), as a novel photoelectric conversion device, offer advantages over conventional photomultiplier tubes including lower noise, smaller size, lower power consumption, and magnetic field immunity. Consequently, NaI(Tl) scintillation detectors designed with SiPMs exhibit benefits of compact size, high efficiency, high sensitivity, and strong anti-interference capability. By optimizing the detector's physical structure and signal processing circuitry, efficient gamma-ray detection has been achieved. This paper presents the design and development of a 1-inch NaI(Tl) detector employing SiPM technology, featuring compact size and low background noise. Testing of the detector's response to a ^{137}Cs source demonstrates an energy resolution of 8.72% for 0.662 MeV gamma rays.

Keywords: NaI(Tl) crystal; SiPM; gamma rays; high energy resolution

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Gamma-ray measurement technology holds significant application value in environmental pollution monitoring [1,4], mineral exploration [2,4], nuclear accident emergency response [3,4], and medical fields. In recent years, with continuous advancements in nuclear technology, high-precision gamma-ray detectors have found widespread application in nuclear science research and the nuclear industry [4]. Due to the strong penetration capability of gamma rays, NaI(Tl) scintillation detectors have become essential tools for gamma-ray measurement and analysis, owing to their high scintillation efficiency, favorable energy resolution, and broad spectral measurement range [5]. Traditional NaI(Tl) detectors typically consist of an NaI(Tl) scintillation crystal, a photomultiplier tube (PMT), and a pre-amplifier (PA) [5]. However, these detectors are generally bulky, require a vacuum environment for photoelectron multiplication, and exhibit poor mechanical robustness and impact resistance, limiting their flexibility in field applications, medical diagnostics, and radiation monitoring. Although photomultiplier tubes have long been the standard photoelectric sensor for NaI(Tl) detectors, their requirements for high-voltage power supplies (ranging from hundreds to thousands of volts), large physical size, and susceptibility to strong magnetic fields constrain portability and practical application scope.

Addressing these limitations, NaI(Tl) detectors based on silicon photomultipliers (SiPM) have attracted considerable research interest in recent years. As a novel semiconductor photoelectric conversion device, SiPM offers advantages including low noise [6], fast temporal response [6], low bias voltage [6], compact size, and magnetic field insensitivity [6], making it widely applicable in modern NaI detector designs. This paper employs Monte Carlo simulation techniques to focus on the design and research methodology for a compact NaI(Tl) detector based on SiPM, encompassing structural dimensions, performance parameters, fabrication methods, and applications in nuclear physics. This research is expected to improve performance in nuclear radiation monitoring, medical diagnostics, and nuclear physics research, providing more reliable tools and methods for human health and environmental protection. Therefore, in-depth study and optimization of this technology represent an important task in the field of radionuclide measurement.

1.1.1 Crystal Selection

The detection principle of scintillation detectors involves incident radiation particles (e.g., gamma rays) entering the scintillator and interacting through photoelectric effect, Compton scattering, and electron-hole pair generation, causing the scintillator to emit photons. Since these photons are too weak to be directly detected, a photomultiplier tube's photocathode is required to convert them into electrons for multiplication and amplification before acquisition by electronic instrumentation [7]. Consequently, parameters such as light yield, emission wavelength, and decay time constitute important criteria for crystal selection [7].

As shown in Table 1, $LaBr_3$(Ce) crystal exhibits high relative light output, indicating that for radiation of the same energy, $LaBr_3$(Ce) can produce more photons. The energy resolution of such crystals can reach 2.6–4.2% (^{137}Cs @ 662 keV), but they are expensive and inherently radioactive, which interferes with radiation measurement processes. NaI(Tl) detectors achieve energy resolution of 7–9% (^{137}Cs @ 662 keV). NaI(Tl) scintillator is one of the most widely used crystals for gamma-ray measurement, offering favorable density characteristics (3.67 g/cm^3), mature manufacturing processes, low cost and ready availability, along with high light yield (38 photons/keV) [7]. Furthermore, as shown in Figure 1 [Figure 1: see original paper] and Figure 3 Figure 3: see original paper, SiPM's optimal spectral response wavelength (430 nm) matches well with NaI(Tl)'s emission wavelength (420 nm), with SiPM photon detection efficiency of approximately 30–40% and superior quantum efficiency compared to PMT [8]. Therefore, a detector coupling SiPM with NaI(Tl) crystal can satisfy the design requirements for efficient detection. Since photon detection efficiency (PDE), defined as the percentage of photons detected by the device relative to photons incident on its surface within a certain time [8], increases with detector surface area, leading to better energy resolution, and considering the need for system miniaturization, a cubic NaI crystal with 1-inch sides was selected.

1.1.2 Monte Carlo Model of the Detector

To verify the design principles, Monte Carlo (MC) simulation methods were employed to calculate detector structural parameters and simulate photon collection and energy resolution for different output surface areas [9]. Figure 2 [Figure 2: see original paper] illustrates the schematic diagram of the detector probe portion composed of NaI scintillator coupled with SiPM.

[Figure 2: see original paper]

As shown in Figure 3 [Figure 3: see original paper], a Monte Carlo model of the sodium iodide detector was constructed in Geant4. The sodium iodide detection system primarily consists of a lead layer, aluminum layer, sodium iodide crystal, glass light guide, and detection surface. In this assembly, the lead layer shields external background radiation; the sodium iodide crystal absorbs gamma rays and converts them into scintillation photons; the magnesium oxide reflective layer collects and reflects scintillation photons; the glass light guide, positioned between the crystal and detection surface, connects the crystal to the detector, reduces total internal reflection at air interfaces, and enables photon collection at the detection surface; the detection surface absorbs scintillation photons, calculates photoelectron numbers based on quantum efficiency corresponding to photon wavelengths, and records these values through the Geant4 program.

The actual energy resolution of the detector is expressed by Equation 1 [10]:
$R_{total}^2 = R_{int}^2 + R_{tr}^2 + R_{det}^2 + R_{dark}^2$
where R_{int} represents the intrinsic resolution of the scintillator, indicating statistical fluctuations in scintillation photon emission [10]; R_{tr} denotes transport resolution, representing contributions to energy resolution from photon transport processes [10]; R_{det} signifies SiPM statistical contributions, indicating statistical fluctuations during photon detection and absorption [10]; and R_{dark} represents dark noise contributions [10].

The model simulates photon transport in the sodium iodide detector but cannot simulate electronic device characteristics such as dark noise in the simplified ideal light collection surface. Therefore, the simulated energy resolution in this study can be obtained through simplification of Equation 1 to yield Equation 2:
$R_{sim}^2 = R_{int}^2 + R_{tr}^2 + R_{det}^2$

By introducing photons into the sodium iodide detector model, the corresponding emission spectrum and transport process of scintillation photons can be obtained. Figure 4(a) [Figure 4: see original paper] shows the simulated emission spectrum of sodium iodide, while 4(b) illustrates the photon transport pathways in the detector model, with green representing gamma rays and yellow representing scintillation photons. Consequently, this model can accurately simulate the statistical fluctuation process R_{int} of scintillation light. The magnesium oxide reflective layer and glass light guide in the model reflect and refract scintillation photons, enabling accurate simulation of R_{tr}. Although Monte Carlo simulation programs cannot model electronic processes, and thus cannot simulate R_{det}, the model can predict detector energy resolution to a certain extent.

Since SiPM has a regular cubic geometry, it can be fully positioned within the crystal bottom surface without requiring special-shaped light cones. The 1-inch sodium iodide crystal selected in this paper can couple with devices up to approximately 18 mm in side length. Models with different light collection surface sizes were established using 18 mm as the maximum value and 3 mm as the gradient step size to obtain detector energy resolution under various detection surface dimensions. The results demonstrate that when the detection surface is square, the variation trends of photon detection efficiency [8] and energy resolution with increasing detection surface side length are shown in Figure 5 [Figure 5: see original paper].

[Figure 5: see original paper]

As indicated in Figures 5(a) and 5(b), photon detection efficiency increases and energy resolution improves with increasing detection surface side length. This occurs because larger detection areas absorb more scintillation photons, enhancing photon detection efficiency in measurements, and photons near the output surface are more likely to be detected rather than refracted or reflected, thereby reducing statistical fluctuations during photon transport and improving energy resolution. To achieve optimal energy resolution while maintaining miniaturization, detailed parameters of the sodium iodide detector obtained through multiple simulations are presented in Table 2 .

SiPM, as a high-resolution, low-noise, high-gain photosensitive device, is commonly used for detecting low-light signals or single-photon events. It integrates thousands to tens of thousands of avalanche photodiodes (APDs) and quenching resistors [6], referred to as pixel units, which are typically arranged in a dense array to form a large photosensitive area. Each unit operates as a photodiode in Geiger mode [6]. When a photon strikes the SiPM photosensitive surface, an avalanche current is generated in each pixel unit's APD, and the accumulated avalanche currents form an output signal whose amplitude is proportional to the number of diodes undergoing avalanche—i.e., proportional to the number of absorbed photons (photon counting). This gain mechanism enables SiPM to detect weak light signals with high signal-to-noise ratio [9]. SiPM resolution depends on multiple factors including pixel unit size, quantity, gain, and electronic noise. Smaller unit sizes generally provide better spatial resolution, while more numerous units and higher gain offer better energy resolution [8].

To achieve optimal detection efficiency and energy resolution, it is essential to ensure that as many photons emitted from the crystal as possible are collected by the SiPM, minimizing photon leakage from the output surface. Therefore, the NaI crystal output surface dimensions should be essentially identical to the SiPM photosensitive area dimensions. Commercially available SiPMs exhibit significant bias voltage variations due to differences in internal structure and manufacturing processes. To meet development requirements and reduce design cost and complexity, this paper adopts the MicroFJ-60035-TSV SiPM from ONSEMI as the detector's photoelectric conversion device. Its bias voltage ranges from 25.2 V to 30.7 V, featuring high photon detection efficiency and timing resolution sensor characteristics. Each device has a photosensitive area of 6 mm × 6 mm, pixel pitch of 35 m, contains 22,292 pixels, operates in a temperature range of -45 °C to 85 °C, and has a package size of 7 mm × 7 mm. To enhance sensitivity and meet the detector's design requirements, four SiPMs are employed with a total photosensitive area of 12 mm × 12 mm, forming a 2$×$2 SiPM array as the detector's photoelectric conversion device.

1.2.1 Probe Packaging Design

To enhance detection efficiency and eliminate air between the scintillator and SiPM, optical coupling agent is employed at the interface. The EJ-560 coupling agent from ELJEN Technology is selected, with specific parameters shown in Table 3 . This coupling agent exhibits high transparency for light within the emission wavelength range of NaI(Tl) crystals [11], as illustrated in Figure 6 [Figure 6: see original paper].

Since NaI(Tl) crystals are hygroscopic, although moisture-proof treatment is applied during manufacturing, crystal processing tolerances necessitate additional moisture protection design. Furthermore, to prevent interference from external light sources entering the probe and affecting the original signal, the probe must be completely light-tight. This is achieved by installing a top cover and rubber gasket on the detector crystal housing for light shielding and moisture protection.

[Figure 7: see original paper]

1.2.2 Signal Readout and Conditioning Circuit

[Figure 8: see original paper]

Figure 8 [Figure 8: see original paper] illustrates the detector signal readout circuit. A bias voltage of 29.5 V is applied to the SiPM cathode, with R42, R43, C52, and C53 serving filtering and decoupling functions.

To produce clearer and more intuitive pulse signals from the detector, the low-noise operational amplifier ADA4625 is employed to sum and amplify the output signals from four SiPMs (S1, S2, S3, S4), as shown in Figure 9 [Figure 9: see original paper]. The ADA4625 is a low-noise, dual-supply operational amplifier that does not generate large input currents from large differential input voltages. Under standard operating conditions, it provides 18 MHz gain-bandwidth, low-noise JFET inputs [12], and 600 Ω load driving capability [13]. The four output signals from the SiPM are positive pulses, which after inverting summation become a single negative pulse signal fed to the second-stage amplification circuit. The output pulse amplitude equals the sum of individual SiPM output pulse amplitudes.

[Figure 9: see original paper]

Since the ADC input voltage range in the digital multichannel analyzer is 0–2 V, the ADA4625 is used for secondary inversion and amplification of the summed signal, converting it to a positive pulse signal. The circuit is shown in Figure 10 [Figure 10: see original paper], where C36 serves as a phase compensation capacitor. The relationship between output and input signals is given by Equation 1:

$$V_{out} = -\frac{R_f}{R_{in}} \cdot V_{in}$$

To prevent op-amp saturation, R22 in parallel with C36 provides a DC path for the charged capacitor, forming a negative feedback loop [14]. The op-amp output pulse amplitude is limited by the supply rails, and programmable gain circuitry is employed to amplify the signal to the appropriate amplitude (0–2 V) for ADC input. Filter capacitors at the op-amp's positive and negative power supply inputs remove power supply noise.

[Figure 10: see original paper]

1.2.3 Power Supply Module Design

The power supply module includes $±$4.5 V supplies for the operational amplifiers and +29.5 V bias high-voltage supply for the SiPM. The +4.5 V supply utilizes the low-noise (3.8 V) low-dropout linear regulator (LDO) TPS7A870, with input voltage range of 1.4–6.5 V, output voltage range of 0.8–5.2 V, and output current of 500 mA. The -4.5 V supply employs the inverting regulator chip LM27761, providing up to 250 mA output current, which satisfies the op-amp power consumption requirements since the quiescent power consumption of op-amps is only tens of milliamperes.

The detector system employs the Micro-FC-60035 SiPM from SensL as the photoelectric conversion device, with bias voltage between 26–30 V. The bias voltage magnitude affects the SiPM multiplication process—higher bias voltage yields higher sensitivity and gain [8]. As shown in Figure 11 [Figure 11: see original paper], the +29.5 V supply utilizes the LT8410 boost converter from Linear Technology. The LT8410 employs a variable peak current and variable off-time control scheme, providing low-ripple voltage output to the load at high switching frequency [15].

[Figure 11: see original paper]

To achieve controllable system gain for detection of different radiation types, gain adjustment is implemented through two methods:

1) **SiPM Bias Voltage Adjustment**
   As shown in Figure 12 [Figure 12: see original paper], the LT8410 provides bias voltage for the SiPM, where the VREF pin supplies a precise 1.235 V reference voltage. The VFBP value can be adjusted through external resistors, with output voltage expressed by Equation 4:

$$V_{out} = V_{REF} \cdot \left(1 + \frac{R_1}{R_2}\right)$$

2) **Programmable Gain**
   Gain adjustment is achieved through the DAC device AD5543 to regulate

the amplification factor of operational amplifiers in the system. Figure 13 [Figure 13: see original paper] shows the gain adjustment window in the host computer software, where commands are issued to configure the gain.

[Figure 13: see original paper]

As shown in Figure 14 [Figure 14: see original paper], the 16-bit D/A converter AD5543 and operational amplifier ADA4817 form a gain control circuit. The AD5543 output and ground are connected to the op-amp's inverting and non-inverting inputs, respectively. The DAC's maximum output current is determined by the reference voltage connected to the VREF pin. By writing different values to AD5543 via SPI protocol, the internal bridge circuit changes resistance values by opening or closing connections, thereby altering the op-amp's feedback resistance to adjust amplification [16].

[Figure 14: see original paper]

2.1 Signal Testing

[Figure 15: see original paper]

Under room temperature conditions with a 140 Bq ^{137}Cs point source placed near the detector, the preamplifier circuit output positive pulse signal is shown in Figure 15 [Figure 15: see original paper]. The amplitude is approximately 670 mV, pulse width at half maximum is about 2.37 s, and signal-to-noise ratio is approximately 29.20 dB. This signal can be distortion-free converted and acquired by the ADC.

2.2 Power Supply Performance Testing

Power supply performance is generally characterized by output voltage value and peak-to-peak ripple voltage. Under room temperature and normal pressure, output voltage was measured using a 4.5-digit multimeter (Fluke 15B), and power supply ripple was measured using a 2 GSa/s bandwidth oscilloscope (Agilent DSO-X2012A) with a probe grounding loop. The measured DC output voltage and peak-to-peak ripple values are shown in Table 4 .

The data in the table indicate stable DC output voltage values with noise within 5 mV.

2.3 Energy Resolution Analysis

The energy resolution R of a spectrometer is commonly expressed by the full width at half maximum (FWHM) of spectral peaks [17]. As mentioned in Section 1.2, factors affecting detector energy resolution primarily include: (1) energy resolution of the radiation source itself; (2) NaI(Tl) crystal energy resolution—statistical fluctuations in the process of energy loss and fluorescent photon production significantly affect crystal energy resolution, which can be improved by enhancing crystal light yield or using larger crystal volumes; (3) SiPM photoelectric conversion and multiplication processes, which are influenced by environmental temperature, bias voltage, dark noise, and crosstalk between adjacent pixel units; and (4) electronic system effects.

Therefore, the energy resolution of a scintillation gamma spectrometer can be expressed by Equation 5:

$$R_{total} = \sqrt{R_{source}^2 + R_{crystal}^2 + R_{SiPM}^2 + R_{electronics}^2}$$

[Figure 16: see original paper]

Figure 16 [Figure 16: see original paper] shows the energy spectrum obtained from the detector under continuous ^{137}Cs source irradiation for 5 minutes at room temperature. The ^{137}Cs full-energy peak is located near channel 715, with the detector achieving approximately 8.72% energy resolution for 662 keV radiation. The measured spectrum exhibits good background and high-energy performance, with low high-energy counts and a clean background spectrum. However, the detector's energy resolution may degrade due to testing environment and methodology, with influencing factors including:

1) For single-crystal NaI(Tl) gamma spectrometers, energy resolution is standardized against the 0.662 MeV photopeak of ^{137}Cs, typically ranging from 7–15%. The source itself constitutes a minor factor affecting detector energy resolution.

2) NaI(Tl) scintillator effects: Thallium (Tl) doping concentration significantly impacts NaI(Tl) performance and energy resolution. Different doping concentrations may result in varying light yields and temporal responses, consequently affecting energy resolution.

3) SiPM-related noise: Correlated noise refers to output from secondary avalanche discharges triggered by previous photons or dark events, primarily consisting of afterpulses and optical crosstalk. Afterpulses occur when carriers trapped in silicon during the avalanche multiplication process are discharged during the APD recovery phase, generating new secondary current pulses with amplitude smaller than the original. Optical crosstalk arises when a primary avalanche in one pixel unit triggers a secondary avalanche in adjacent units (Optical Crosstalk, OC), which increases with bias voltage.

4) Electronic noise: Active devices such as operational amplifiers in preamplifier and signal conditioning circuits, along with passive components (resistors, capacitors, inductors), introduce noise that degrades energy resolution. These noise sources include: (i) thermal noise from random electron motion due to temperature in electronic components; (ii) distributed parameter circuit noise from electromagnetic interference and signal propagation scattering in printed circuit boards (PCBs); (iii) quantization error

noise from ADCs; and (iv) power supply noise from voltage and current fluctuations.

For clear experimental demonstration, this study compares the measured spectrum with that from a Hamamatsu CH249-02 sodium iodide detector. The Hamamatsu detector employs a cylindrical NaI crystal (2-inch diameter, 3-inch height) with an R1924A photomultiplier tube, pulse output amplitude of approximately 0.6 V, and 12 V power supply. Under identical temperature conditions and connected to the same detection system, the obtained spectrum is shown in Figure 17 [Figure 17: see original paper]. The ^{137}Cs full-energy peak is located near channel 652, with energy resolution of approximately 8.82% for 662 keV radiation. This comparison demonstrates that the detector designed in this study, using a 1-inch NaI crystal and SiPM photoelectric conversion device, achieves miniaturization while maintaining favorable energy resolution.

[Figure 17: see original paper]

Conclusion

For the compact SiPM-NaI(Tl) detector, this paper first established a radiation source physical model and NaI detector system based on scintillation light transport in the GEANT4 platform. Through theoretical simulation of photon collection and energy resolution for different output surface areas, the optimal NaI crystal dimensions were determined. Subsequently, signal readout circuits were designed and debugged, and the ^{137}Cs point source energy spectrum was measured using a digital multichannel analyzer. Comparison with the spectrum measured by a Hamamatsu NaI scintillation detector demonstrates that the SiPM-NaI(Tl) detector designed in this study achieves 8.72% energy resolution for ^{137}Cs (@662 keV) radiation, indicating that the detector maintains good energy resolution while achieving the design goal of miniaturization. However, since SiPM and analog circuits are significantly affected by temperature, which can cause spectral drift [18] and impact energy resolution, this study has limitations. Future work will investigate temperature effects on the SiPM signal readout system and implement temperature compensation [19].

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