A Compton scattering method for the high flux energy spectrum measurement of inverse Compton scattering gamma-ray sources

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Abstract

The Very Compact Inverse Compton Scattering Gamma-ray Source (VIGAS) is a gamma-ray facility under construction at Tsinghua University. It has the ability to produce more than 10^6 quasi-monoenergetic gamma photons per pulse within 10 ps. Due to ultra-short pulse length, conventional detectors and methods cannot directly measure the energy spectrum of the VIGAS. In this study, we employ the Compton scattering method to reduce the photon flux and collect the scattered photons in a specific direction using high-purity germanium (HPGe) detectors. The central energy and energy spread of the incident gamma rays can be determined by analyzing the spectrum of the scattered photons. To correct for the Doppler broadening effect during the Compton scattering process, both the error transfer formula method and the neural network method are developed. Monte Carlo simulations show that the energy spectrum of the VIGAS can be reconstructed accurately by both the two methods, with a central energy accuracy better than 0.1% and energy spread accuracy better than 3%. A proof-of-principle experiment conducted at the Shanghai Laser Electron Gamma Source (SLEGS) validates the feasibility of the Compton scattering-based reconstruction method for energy spectrum measurements.

Full Text

A Compton Scattering Method for High-Flux Energy Spectrum Measurement of Inverse Compton Scattering Gamma-Ray Sources

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The Very Compact Inverse Compton Scattering Gamma-ray Source (VIGAS) is a gamma-ray facility under construction at Tsinghua University with the capability to produce more than 10^6 quasi-monoenergetic gamma photons per pulse within 10 ps. Due to this ultra-short pulse length, conventional detectors and methods cannot directly measure the energy spectrum of VIGAS. In this study, we employ the Compton scattering method to reduce the photon flux and collect scattered photons in a specific direction using high-purity germanium (HPGe) detectors. The central energy and energy spread of the incident gamma rays can be determined by analyzing the spectrum of the scattered photons. To correct for the Doppler broadening effect during the Compton scattering process, we develop both an error transfer formula method and a neural network method. Monte Carlo simulations show that the energy spectrum of VIGAS can be reconstructed accurately by both methods, with a central energy accuracy better than 0.1% and energy spread accuracy better than 3%. A proof-of-principle experiment conducted at the Shanghai Laser Electron Gamma Source (SLEGS) validates the feasibility of the Compton scattering-based reconstruction method for energy spectrum measurements.

Keywords: Compton scattering, gamma ray, high-purity germanium detector, Monte Carlo simulation, Doppler broadening

INTRODUCTION

Inverse Compton scattering (ICS) gamma-ray sources can generate high-flux gamma-ray beams with energies reaching several tens of MeV. Determining the energy spectrum of ICS gamma-ray sources is a critical aspect of facility characterization. Facilities based on electron storage rings, such as HIγS [1, 2], NewSUBARU [3, 4], and SLEGS [5, 6], typically employ high-purity germanium (HPGe) detectors for direct gamma-photon energy measurements because the gamma rays produced by these facilities are continuous and their beam intensity is adjustable. However, some linear-accelerator-based ICS facilities, such as ELI-NP [7] and VIGAS [8], produce gamma rays in pulses with typical pulse lengths of 10 ps. The pulse pile-up effect caused by this ultra-short pulse length makes it impossible to directly measure the energy spectrum of these facilities.

In this study, we develop a method for determining the gamma-ray energy spectrum characterized by ultra-short pulse length. The Very Compact Inverse Compton Scattering Gamma-ray Source (VIGAS) is an ongoing gamma-ray facility project at Tsinghua University, designed for advanced X/gamma-ray imaging applications. By optimizing the laser and accelerator design, VIGAS can generate quasi-monoenergetic gamma rays within a very compact space [8, 9]. To assess the gamma-ray quality produced by VIGAS, precise determination of both the central energy and the root-mean-square (rms) energy spread of the gamma-ray photons is essential. Owing to the high photon flux density within each short pulse, conventional detectors and methods are unable to directly measure the gamma-ray energy of VIGAS.

Two measurement approaches are typically employed: the attenuation method [10–12] and the Compton scattering method [13–15]. The attenuation method reconstructs the incident spectrum by utilizing the energy dependence of photon attenuation coefficients. However, for gamma rays in the 1 MeV to 5 MeV range, the attenuation coefficients show relatively weak variation with energy for most materials [16], resulting in inadequate spectral resolution for precise measurements. The Compton scattering method has been implemented at ELI-NP for energy spectrum measurement in the range of 0.2 MeV to 19.5 MeV through recoil electron detection [17, 18]. Compared to recoil electrons, detection of scattered photons requires no vacuum environment and is easier to set up. This work investigates the Compton scattering method for determining the VIGAS energy spectrum via scattered photon energy measurements.

II. ENERGY SPECTRUM MEASUREMENT SYSTEM OPTIMIZATION

This study aims to accurately determine the energy spectrum of VIGAS. As summarized in Table 1 , VIGAS is designed to generate quasi-monoenergetic gamma rays with energies ranging from 0.2 MeV to 4.8 MeV (rms spread <1.5%) at a repetition rate of 10 Hz. The VIGAS can deliver a high photon yield exceeding 10^6 photons/pulse with an ultra-short pulse length (<10 ps), presenting unique measurement challenges due to the extreme instantaneous flux.

TABLE 1. Main specifications of VIGAS

Specifications	Value
Energy range (MeV)	0.2–4.8
Relative energy spread	<1.5%
Repetition (Hz)	10
Photon flux (s^{-1})	$>10^6$

The Compton scattering method is shown schematically in Fig 1 [Figure 1: see original paper]. The incident gamma rays undergo Compton scattering in an aluminum target, chosen for its low atomic number (Z=13) and machinability. The scattered photons are collimated at a predetermined angle using two lead apertures: one positioned near the scattering target and the other preceding the detector. A HPGe detector precisely measures the energy spectrum of the collimated scattered photons, enabling the spectral reconstruction of the incident beam.

To improve the efficiency and measurement precision of the Compton scattering method, several critical parameters must be optimized: (1) the scattering angle , which determines the energy-angle relationship of the scattered photons; (2) the thickness t of the aluminum scattering target, which affects the scattered photon yield; and (3) the width w of the lead collimator slits, which governs the angular acceptance and energy resolution of the system. These parameters collectively influence the signal-to-noise ratio and overall measurement accuracy of the spectral reconstruction.

By applying the error propagation method (described in Section III) to the simulation results, we determine the accuracy of the reconstructed energy spread across different scattering angles, with the results presented in Fig 2 [Figure 2: see original paper]. For photons within the VIGAS energy range, the Compton scattering method with scattering angles below 40° yields accurate results. The reconstructed central energy maintains agreement with the actual value within 0.1% for all scattering angles. Fig 3 [Figure 3: see original paper] shows the normalized detection efficiency as a function of scattering angle for different incident energies, demonstrating a decreasing trend with increasing angle. Also considering the experimental spatial constraints, we selected a scattering angle of 30°.

The detection efficiency of the Compton scattering method is proportional to both the scattering target thickness and the collimator slit width. To mitigate pulse pile-up effects and ensure single-scattered-photon detection per pulse, we performed systematic simulations across multiple target thicknesses and collimator slit widths. Based on the simulation, a 2 mm-thick aluminum scattering target paired with a 4 mm-wide collimator slit was identified as the optimal configuration. Under these conditions, the HPGe detector in the VIGAS system is expected to detect approximately one photon per pulse across its operational energy range.

In summary, the simulation configuration is shown in Table 2 . Generally, increasing the counts in the scattered spectrum reduces the statistical uncertainty, thereby improving measurement precision. However, the 10 Hz repetition rate of VIGAS imposes a constraint on the maximum achievable counting statistics. The simulated scattered spectrum in this study contains 10,000 counts for the full-energy peaks, corresponding to approximately 1 hour of VIGAS operation time.

TABLE 2. Simulation configuration

Specifications	Value
Scattering angle (°)	30

Specifications	Value
Target thickness (mm)	2
Collimation slit width (mm)	4
Distance between target and detector (m)	1
HPGe detector resolution	1 keV @ 122 keV, 2 keV @ 1332 keV
HPGe detector relative efficiency	40%

Fig 4 [Figure 4: see original paper] illustrates the impact of various factors on the energy spread of the scattered spectrum. The simulations consider incident photon energies of 200 keV, 2 MeV, and 4 MeV, each with an energy spread of 1%. The blank reference group excludes three key effects: the energy resolution of the HPGe detector, the scattering angle uncertainty, and the Doppler broadening of the scattered photon energy. Within the VIGAS energy range, Doppler broadening emerges as a non-negligible contributor to the scattered spectrum's energy spread.

We generated scattered spectra via Monte Carlo simulations and investigated spectral reconstruction methods to determine the incident photons' central energy and energy distribution. The simulations employ Geant4 [19, 20] as the Monte Carlo framework. For electromagnetic interactions, we utilize the Livermore cross-section database with the relativistic impulse approximation [20, 21]. In the relativistic impulse model [21–23], the energy of the scattered photon is also affected by the initial momentum of the electron. The electron momentum distribution outside the nucleus is characterized by the Compton profile. The Compton profile used in this study is calculated by F. Biggs [24].

III. INCIDENT SPECTRUM RECONSTRUCTION METHOD

A. Central Energy

In the free electron model, the relationship between the energy of the incident photon and the energy of the scattered photon is given by the Compton scattering equation [13]:

$$E' = \frac{E}{1 + \frac{E}{m_ec^2}(1 - \cos\theta)}$$

where E is the energy of the incident photon, E' is the energy of the scattered photon, m_e is the rest mass of the electron, θ is the scattering angle, and c is the speed of light in vacuum. Through analysis of the scattered photon spectrum, we can determine the central energy E' of the scattered radiation through Eq.1.

To validate the accuracy of the reconstructed central energy, we performed simulations using photons with incident energies of 0.2 MeV, 1 MeV, 2 MeV, 3 MeV and 4 MeV, each having an energy spread of 1%. The resulting scattered spectra were analyzed to determine the central energies, with the complete results presented in Fig 5 [Figure 5: see original paper]. The results show that the relative deviation of the central energy measurement is less than 0.02%. This precision satisfies the VIGAS measurement accuracy requirements.

B. Energy Spread

The VIGAS gamma-ray beams exhibit an intrinsic energy spread of approximately 1.5%. The scattered spectra undergo additional broadening due to Doppler effect and systematic error in the experimental system. To address these effects, we develop two methods: the error transfer formula method and the neural network image recognition method.

1. Error Transfer Formula Method The energy spread relationship between scattered and incident photons can be derived through error propagation analysis. According to Eq.1, the uncertainty in scattered photon energy originates from both the incident photon energy spread and the scattering angle uncertainty:

$$\frac{\Delta E'}{E'} = \frac{\Delta E}{E} \cdot \frac{E'}{E} + \Delta\theta \cdot \frac{\sin\theta}{1-\cos\theta}$$

To validate the accuracy of Eq.2, we performed simulations using 2 MeV photon beams with energy spreads of 1%, 1.25%, 1.5%, 1.75% and 2%. The full-energy peak in the scattered spectrum was fitted with a Gaussian distribution. The fitted parameters σ (standard deviation)/μ (mean) were substituted into Eq.2 as $\Delta E'/E'$. $\Delta\theta/\theta$ was obtained through the geometric configuration adopted in the simulation. The calculation results are shown in Fig 6 [Figure 6: see original paper]. Since Eq.1 does not consider the impact of Doppler broadening, the precision of the calculation results is poor. The calculation results exhibit a deviation of more than 7.5% and an uncertainty greater than 8%.

The full-energy peak in the spectrum exhibits non-Gaussian characteristics due to Doppler broadening effects and collimator width constraints as shown in Fig 7 [Figure 7: see original paper]. Consequently, the σ parameter obtained through Gaussian fitting is inadequate for uncertainty propagation in the equation. To characterize the combined effects of Doppler broadening and the scattering angle uncertainty, a parameter C is selected and defined as $\Delta E_s/E_s$, where ΔE_s and E_s are the root mean square (RMS) and the central energy of the full energy peak in the simulated scattered spectrum, respectively, under the condition of monoenergetic incident photon energy. As a result, Eq.2 can be rewritten as:

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{E}{E'}\right)^2 \left[\left(\frac{\Delta E'}{E'}\right)^2 - C\right]$$

To benchmark the validity of Eq.3, we simulated scattered spectra for incident energies of 200 keV, 2 MeV, and 4 MeV, parameterized with relative energy spreads ranging from 1% to 2% in 0.25% increments. The RMS/E_s (central energy of the full-energy peak) is substituted into Eq.3 as $\Delta E'/E'$. The results are illustrated in Fig 8 [Figure 8: see original paper]. The incident energy spread uncertainty was calculated to be better than 3% using Eq.3.

2. CNN-Based Image Recognition Method To complement the traditional error propagation analysis, we employ a convolutional neural network (CNN) to process the full-energy peak as one-dimensional image data [25–29]. This machine learning approach directly maps spectral features to the incident energy spread, providing an independent validation method.

Our training data comprises Geant4-simulated scattered spectra labeled by their incident energy spreads. Each full-energy peak (1\$×256*vector*)*isreformattedasa*16×\$16 image for CNN processing, preserving spectral integrity while leveraging spatial feature extraction capabilities. The architecture of our convolutional neural network is illustrated in Fig 9 [Figure 9: see original paper].

For each incident energy $E_0 = 200$ keV, 2 MeV, and 4 MeV, we generated a dedicated training dataset consisting of 500 scattered spectra, each containing over 1×10^6 counts. These spectra share the same E_0 but cover energy spreads ($\Delta E/E_0$) ranging from 0.25% to 2.25% in 0.01% increments.

The trained networks were validated against independent test sets with energy spreads of 1%, 1.25%, 1.5%, 1.75%, and 2%. The network's performance in predicting energy spreads is quantitatively shown in Fig 10 [Figure 10: see original paper]. The neural network achieves an output uncertainty of less than 3.5%, demonstrating accuracy comparable to that of the conventional error transfer formula method.

IV. VALIDATION EXPERIMENT

Validation experiments for Compton scattering spectrum measurement were performed at the Shanghai Laser Electron Gamma Source (SLEGS) facility [5]. The SLEGS beamline generates quasi-monochromatic gamma-ray beams spanning 0.5 MeV to 20 MeV with a characteristic energy spread of ~5%. SLEGS modulates the output gamma-ray energy by adjusting the collision angle between electrons and laser beams. Consequently, the photon yield decreases at lower gamma-beam energies, particularly when the energy falls below 5 MeV. Considering the output energy range of the VIGAS system, we selected 5.5 MeV as the primary energy point for our measurements [30]. The gamma-ray spectrum was measured using a BGO detector installed on the SLEGS beamline [6], as shown in Fig 11 [Figure 11: see original paper]. When the SLEGS gamma beam was tuned to a central energy of 5.5 MeV, the measured energy spread was 372 keV.

The Compton scattering method was originally designed for short-pulse, high-brightness gamma sources like VIGAS. However, SLEGS generates continuouswave gamma radiation with a photon yield approximately 1% of VIGAS's design specifications, resulting in significantly compromised detection efficiency in scattering measurements. To enhance detection efficiency, a 10 mm thick Pb target was used as the scattering target. The setup included 5 cm thick lead bricks for collimation, with a collimator slit width of 1 cm. Scattered spectra were acquired using a HPGe detector (specifications detailed in Table 2). The electronic readout system comprised a CAEN N8064 high-voltage power supply for detector biasing and a CAEN 1730 digitizer module for signal acquisition. Both the amplitude and timing characteristics of the detector pulses were recorded to enable comprehensive spectrum analysis. The experimental configuration is schematically presented in Fig 12 [Figure 12: see original paper].

V. EXPERIMENTAL RESULTS

Initial measurements were performed with the incident beam at a central energy of 5.5 MeV. The scattered spectra were acquired at three scattering angles: 20°, 33°, and 40° (see Fig 13 [Figure 13: see original paper]), with each angle requiring a 3 hour acquisition time. The angular dependence of the Compton peak positions demonstrates the successful detection of Compton-scattered photons.

With the HPGe detector fixed at $\theta = 33°$, we acquired scattered spectra for four incident beam energies: 5.5 MeV, 7.2 MeV, and 9.3 MeV. Each energy spectrum was acquired over a 3 hour acquisition period. Spectra for 5.5 MeV, 7.2 MeV, and 9.3 MeV are presented in Fig 14 [Figure 14: see original paper]. The full-energy peaks were fitted using:

$$y = A \exp\left[-\frac{(x - E_S)^2}{2\sigma^2}\right] + mx + b$$

where A is the peak area (counts · keV), E_S is the central energy of scattered photons (keV), σ is the standard deviation (keV), m is the background slope (counts/keV), and b is the background intercept (counts).

Using the "Gaussian+linear" fitting model, we determined the central energies E_S of scattered photons. The incident energies E_0 were reconstructed using Eq. 1, with the results shown in Fig 15 [Figure 15: see original paper]. Due to the limited peak counts, the relative uncertainties of the reconstructed central energies were 4% for energies below 8 MeV and increased to 8% at 9.3 MeV.

To validate the energy spread reconstruction method, we performed a 24 hour measurement at $\theta = 33°$ using a 5.5 MeV incident beam. The resulting scattered spectrum is shown in Fig 16 [Figure 16: see original paper]. The spectrum clearly shows both the Compton full-energy peak and a secondary 511 keV peak originating from electron-positron annihilation processes. The full-energy peak in the measured spectrum was fitted using Eq. 4, yielding a central energy $E_S = 2020$ keV with an RMS width of $\sigma = 59.8$ keV. By considering the Doppler broadening and the collimator constraint, the reconstructed incident energy spread was determined to be 395 keV ± 28 keV. This result is in agreement with the nominal energy spread of the 5.5 MeV incident gamma beam ($\Delta E_{\text{nominal}} = 372$ keV), with a relative deviation of 6.2%.

VI. CONCLUSION

This study presents a Compton scattering-based energy spectrum measurement method for the VIGAS system, developed through Monte Carlo simulations and experimental validation. The key parameters of the method were determined based on the characteristics of the VIGAS light source. Through simulation we demonstrate that Doppler broadening significantly contributes to the energy spread of the scattered spectrum, necessitating its explicit incorporation into the analytical framework. We conducted simulations to verify the reconstruction method. The central energy of the incident spectrum was calculated from the scattered spectrum's central energy using the Compton scattering equation, with the simulation achieving an accuracy of 0.1%. The incident energy spread was reconstructed through two complementary approaches: the analytical method and the image recognition method using a convolutional neural network (CNN). The reconstruction precision reached 3% for the analytical method and 3.5% for the CNN-based approach, indicating the viability of both methods for energy spread determination.

Experimental validation at the SLEGS facility confirmed the method's feasibility despite photon yield limitations: an average 4% deviation in central energy reconstruction across multiple energies and a 6.2% deviation in energy spread determination for the 5.5 MeV case (24-hour measurement).

The Compton scattering experimental platform has been fully established. Four HPGe detectors, independently developed by Tsinghua University, will be deployed for scattered spectrum measurements to enhance experimental detection efficiency. Upon the official beam delivery from VIGAS, this experimental platform will enable the experimental validation of the proposed method's precision for spectral measurements of short-pulse, high-brightness gamma-ray sources.

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Note: Figure translations are in progress. See original paper for figures.