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Comparison of modeled and measured performance of a GSO crystal as gamma detector



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ABSTRACT

We have modeled, tested, and installed a large, cerium-activated Gd_2SiO_5 crystal scintillator for use as a detector of gamma rays. We present the measured detector response to two types of incident photons: nearly monochromatic photons up to 40 MeV, and photons from a continuous Compton backscattering spectrum up to 200 MeV. Our GEANT4 simulations, developed to determine the analyzing power of the Compton polarimeter in Hall A of Jefferson Lab, reproduce the measured spectra well.

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1. Introduction

Cerium-activated gadolinium oxyorthosilicate ($\text{Gd}_2\text{SiO}_5\text{:Ce}$, or GSO) [1] is a scintillator with a high light output and fast decay time relative to many other commonly used scintillating crystals, e.g. $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO). These properties, along with the crystal's non-hygroscopic nature, its relative ease of growth, and its radiation hardness, have made it a popular choice for a number of detection applications. Its most high-profile use is in positron emission tomography [2], where detectors are optimized for 511 keV photons, but GSO scintillators have also been used to detect protons [3], charged leptons, and pions [4].

In 2009, a GSO crystal with Ce:0.5 mol% doping, grown by Hitachi Chemical and read out with a photomultiplier tube (PMT), was adopted as a gamma detector for the upgraded Compton polarimeter [5] in Hall A [6] of the Thomas Jefferson National Accelerator Facility (Jefferson Lab) [7]. This device exploits Compton scattering to make a continuous measurement of the longitudinal electron-beam polarization, a vital parameter for a significant portion of Hall A's experimental program. Integration of the energy that backscattered photons deposit

in this crystal allows such a measurement to be made with precision better than 1% [5]. With a Compton-laser wavelength of 1064 nm, as in the Jefferson Lab data described in this work, the maximum energy of a Compton-backscattered photon may range from 18 to 580 MeV, depending on the beam energy chosen for the experiment (1–6 GeV).

Uncertainties in the detector response to incident gammas are important potential sources of systematic error. In particular, the energy-weighted integration is sensitive to non-linearities in the response. To reduce these uncertainties, a model was developed using the GEANT4 simulation toolkit [8] and was compared to calibration data, taken at two facilities, with incident gammas from 20 to 200 MeV. Section 2 describes the Compton polarimeter and the fundamental simulation method as applied to single-arm Compton photon data at Jefferson Lab. Section 3 discusses further tests at Jefferson Lab using photons tagged by coincident Compton-scattered electrons. In Section 4, we give the results of tests with nearly monoenergetic photon beams in the 20–40 MeV range at the High-Intensity γ Source (HI γ S) [9], a facility on the Duke University campus that produces gammas by Compton backscattering of light stored in a free-electron laser cavity.

2. Hall A Compton polarimeter and simulation method

In the Compton polarimeter in the Hall A beamline at Jefferson Lab, the polarized electron beam is routed through a four-dipole magnetic chicane (Fig. 1). In the center of the chicane, the beam

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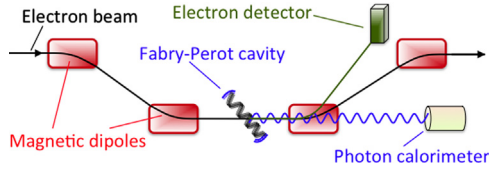


Fig. 1. Schematic of the Hall A Compton polarimeter [5].

interacts with circularly polarized laser light in a high-finesse Fabry-Pérot cavity. Compton-backscattered photons pass undeflected through the 1-in. gap [10] in the third dipole; the GSO calorimeter is located on this direct path. A silicon-microstrip detector (Section 3) detects Compton-scattered electrons, which are deflected through a larger angle than the unscattered majority of the beam. The Fabry-Pérot cavity is periodically taken out of resonance, nearly eliminating Compton-scattering events in the cavity and allowing a direct background measurement. During typical running, the dipole fields are controlled via feedback from a beam-position monitor in the chicane, so as to maintain a stable beam position.

Light from the GSO calorimeter is collected in a 2-in., 12-stage BURLE Industries RCA 8575 PMT, with a base customized for maximum linearity of response. The data-acquisition system is based on a 12-bit Struck SIS3320 flash analog-to-digital converter, modified to integrate the input signal over an externally timed window and configured to sample at 200 MHz. In addition to performing this onboard integration, the SIS3320 card records all samples from the window in one of two internal buffers. Time-stamps from photon- or electron-detector triggers, recorded in a CAEN V830 latching scaler, allow the retention of some information about individual pulses. For a prescaled sample of pulses, the numerical sum of samples from the programmable readout window is recorded in the datastream; the energy of the incident photon can be retrieved from this pulse integral. For a smaller number of pulses, all the samples for the readout window are written to disk, allowing pulse-shape analysis [5]. It is also possible to trigger the system at regular intervals that are uncorrelated with photon pulses, allowing the study of pileup events. These triggers are generated either in software or with a remotely programmable function generator.

The GEANT4 Monte Carlo (MC) simulation of the GSO crystal response was performed with version 4.9.4, patch 03. The MC begins with the generation of a beam of simulated photons to match the experimental beam. To reproduce a Compton-backscattered beam, simulated photons of various energies are generated with probabilities weighted by the Compton scattering cross-section for the specific initial electron and laser-photon energies of the planned experiment. No other electron-beam properties are included in the model. The simulated photons are then allowed to interact with beamline items downstream of the dipole; in the standard Hall A installation, this includes a 0.5-mm-thick stainless-steel vacuum window, a 1-mm-thick, 4-cm-diameter lead synchrotron-radiation filter, and a 5-cm-thick, 8-cm-diameter lead collimator with an interchangeable aperture up to 2 cm in diameter. Thicker lead filters were available but were shown in simulation to distort the energy spectrum. The final item in the beamline is the GSO crystal, a cylinder 6 cm in diameter and 15 cm (10.9 radiation lengths) long; Table 1 lists the other crystal properties used in the MC. Fig. 2 histograms the locations where photons in the simulation first interact with matter.

GEANT4 modeling of the gamma shower relies on the cross-section σ for gamma conversion into an (e^+, e^-) pair; for gamma energies between 1.5 MeV and 100 GeV, the parameterization is accurate to within 5%, with a mean accuracy of 2.2% [11]. Electromagnetic interactions [12] are modeled based on the Livermore

Table 1

GSO:Ce (0.5 mol%) properties used in simulation.

Property	Value	Reference
Density	6.71 (g/cm ³)	[14]
Radiation length	1.38 (cm)	[3]
Attenuation length	340 (cm)	Estimated from [3]
Birks' constant	5.25(μm/MeV)	[15]

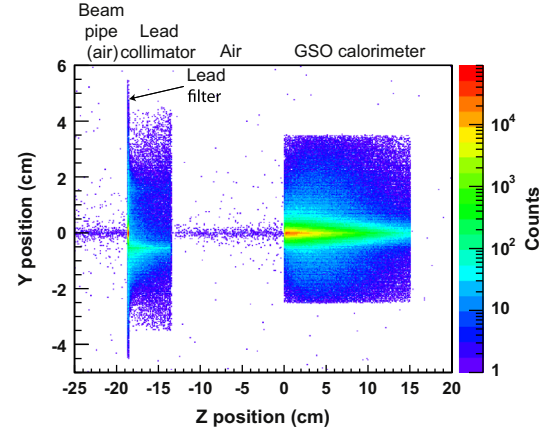


Fig. 2. Histogram of positions of the first interaction point of incident photons in the Hall A Compton gamma beamline, as determined by the GEANT4 MC. The z position is measured along the central axis of the incident Compton-scattered photons; the y axis is vertical. In this figure, the central axes of the calorimeter and of the 2-cm aperture of the collimator are offset by 0.5 cm from the gamma beam, reflecting conditions during one run period.

physics list; substituting the standard electromagnetic physics list or the Penelope physics list did not produce noticeable differences. Hadronic interactions are based on the QGSP_BIC physics list; other packages, not designed for this energy range, gave a discrepancy of about 0.5% in the average energy deposit. The combined non-linearity of the photomultiplier tube and front-end electronics was measured in situ [13], and the resulting functional form is an input to the simulation.

An optical extension to this basic simulation follows the path of each scintillation photon produced in the electromagnetic shower from an incident Compton-scattered photon. This package approximates the polished GSO surface as perfectly smooth and includes the aluminum-foil detector wrapping (with a modeled reflectivity of 0.9) and the efficiency of the PMT photocathode. The output of the MC is the number of photoelectrons produced in the simulated photocathode. The resulting spectrum shows non-Gaussian smearing due to optical effects such as shower leakage from the crystal and the dependence of photon-collection efficiency on the initial interaction position. However, it takes 6000 times longer to generate a given number of events with the optical package than it does without the package, which is prohibitive for some simulation tasks.

Spectra simulated under Jefferson Lab conditions must be modified to take into account pileup, in which two or more pulses arrive and are integrated during the readout window for a single trigger. This correction is determined experimentally based on periodically triggered snapshots of the readout window, which give the random-event rate and the spectrum of energy deposited by random pulses during such a window. For spectra from electron-photon coincidence data (Section 3), it is sufficient to use this spectrum to add random, pileup pulse integrals to those of simulated Compton-scattered photons. For photon-arm singles data, however, the correction is complicated by the possibility of pileup between two Compton events; a naive pileup correction

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