Development of a Hard X-Ray Polarimeter for Gamma-Ray Bursts

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Abstract. We describe recent work on the development of a Compton scatter polarimeter for measuring the polarization of hard X-rays (100–300 keV) from astrophysical sources. Results from measurements with a laboratory prototype are summarized, along with comparisons to Monte Carlo simulations. We also present a new design concept that envisions a complete polarimeter module on the front end of a 5-inch position-sensitive PMT. Although the emphasis of our effort is measuring hard X-ray polarization in solar flares, our design has the advantage that it is sensitive over a rather large FoV (> 1 sr), a feature that makes the design especially attractive for γ-ray burst studies.

INTRODUCTION

The measurement of hard X-ray polarization in γ-ray bursts would add yet another piece of information in our effort to resolve the true nature of these enigmatic objects. Here we report on the development of a hard X-ray polarimeter for solar flares that, because of its relatively large FoV, may be useful in studies of γ-ray bursts.

The basic physical process used to measure linear polarization of hard X-rays (100–300 keV) is Compton scattering. The measurement is based on the fact that the incident photons tend to be scattered at right angles to the incident electric field vector. A Compton scatter polarimeter consists of two detectors that are used to determine the energies of both the scattered photon and the scattered electron. One detector (the *scattering detector*) provides the medium for the Compton interaction to take place. This detector must be designed to maximize the probability of a single Compton interaction with a subsequent escape of the scattered photon. The primary purpose of the second detector (the *calorimeter*) is to absorb the full energy of the scattered photon. To be recorded as a polarimeter event, an incident photon Compton scatters from one (and only one) of the scattering detectors into the central

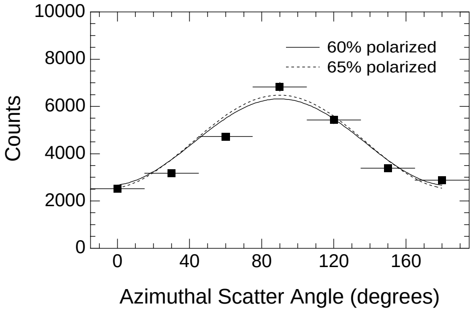

FIGURE 1. The prototype response to an on-axis polarized beam. The smooth curves represent simulation results.

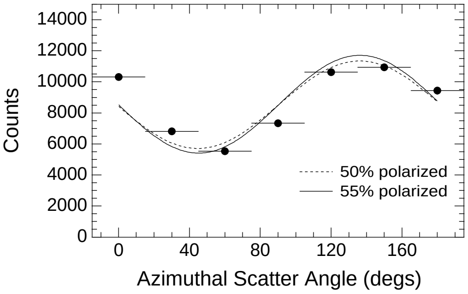

FIGURE 2. The prototype response with the polarization vector rotated 45° with respect to that in Figure 1.

calorimeter. The incident photon energy can be determined from the sum of the energy losses in both detectors and the scattering angle can be determined by the azimuthal angle of the associated scattering detector. When the polarimeter is arranged so that the incident flux is parallel to the symmetry axis, unpolarized radiation will produce an axially symmetric coincidence rate. If the incident radiation is linearly polarized, then the coincidence rate will show an azimuthal asymmetry whose phase depends on the position angle of the incident radiation's electric vector and whose magnitude depends on the degree of polarization.

LABORATORY PROTOTYPE

In an earlier paper, we discussed a polarimeter design consisting of a ring of twelve individual scattering detectors (composed of low-Z plastic scintillator) surrounding a single NaI calorimeter [1]. The characteristics of this design were investigated using a series of Monte Carlo simulations (based on a modified version of GEANT). We have recently prototyped this design in the laboratory to validate our Monte Carlo code. For prototype testing, we set up a semicircular array around a central NaI detector, eliminating the redundancy and simplifying the hardware and associated electronics. Seven plastic scintillators (each 5.5 cm × 5.5 cm × 7.0 cm in size) were positioned at a radius of 15 cm from a 7.6 cm diameter × 7.6 cm high cylindrical NaI(Tl) detector.

Polarized photons were generated by Compton scattering photons from a radioactive source [2]. The exact level of polarization is dependent on both the initial photon energy and the photon scatter angle. The use of plastic scintillators as a scattering block permits the electronic tagging of the scattered (polarized) photons. This is used to provide a coincidence signal to the polarimeter. For our laboratory measurements we used a ^{137}Cs source to generate a beam of polarized 288 keV photons.

The laboratory data (Figure 1) led to a measured polarization value of 64.0%(±3.0%), in good agreement with the estimated value of 50-60% based on analytical estimates [3]. This result demonstrates: a) the ability of a simple Compton scatter polarimeter to measure hard X-ray polarization; b) the ability of our Monte Carlo code to predict the polarimeter response; and c) the ability to generate a source of polarized photons using a simple scattering technique. In another laboratory measurement (Figure 2), the plane of polarization of the incident beam was rotated $\sim 45^\circ$ with respect to that used in the first set of data. The measured shift of 50.4° in the polarization vector is consistent with the uncertainties in our experimental setup.

A NEW DESIGN CONCEPT

There are at least two possible means of improving the polarimeter performance: 1) by more precisely measuring the scattering geometry of each event; and 2) by rejecting those events that undergo multiple Compton scattering within the scattering elements. (Our simulations indicate that roughly 30-40% of the events recorded in the prototype polarimeter as valid events involved multiple scattering within a single scatter element.) Improvements in either area will lead directly to a more clearly defined modulation and, therefore, a better polarization sensitivity.

We have developed a new design that places an entire device on the front end of a single 5-inch diameter position-sensitive PMT (PSPMT) [4]. A bundle of scintillation fibers (each with a cross section of 4 mm × 4 mm) provides the improved spatial resolution in the scattering elements. The bundle is in the form of an annulus with an outside diameter of 10 cm and an inside diameter of 4 cm. A 2 × 2 array of 1 cm inorganic scintillators is positioned within the annulus, each scintillator being coupled to their own independent PMT for light collection and signal timing. Figure 3 shows a schematic view of such an assembly.

Monte Carlo simulations have been used to determine the characteristics of this design. Figures 4 and 5 show the modulation factor and the effective area, respectively, as a function of energy. The low energy response is very sensitive to the energy threshold in the fiber array. Figure 6 shows the off-axis response of the design, which suggests a useful FoV of at least one steradian.

SUMMARY

We anticipate that this design would be used in the context of a (not necessarily contiguous) array of polarimeter modules. Figure 7 shows the sensitivity of an array of 16 modules, suggesting that a sensitivity level of about 15% may be achieved for the strongest γ-ray bursts.

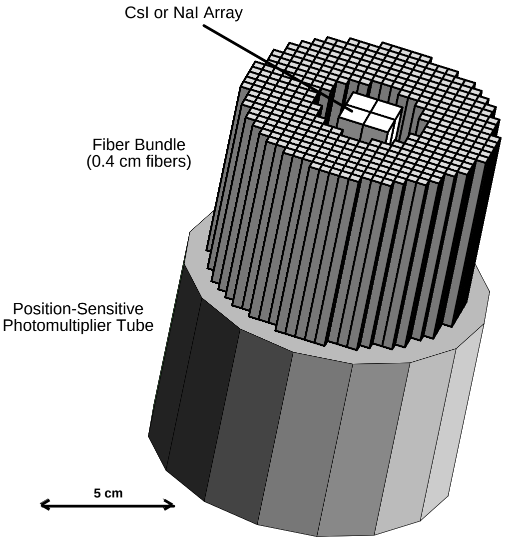

FIGURE 3. Schematic diagram of a polarimeter module.

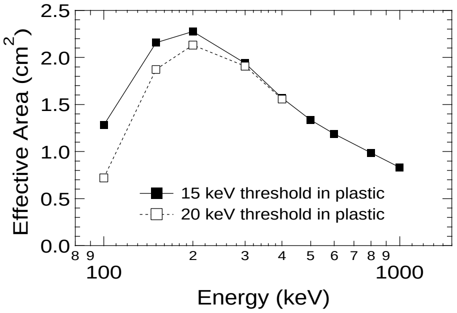

FIGURE 4. Effective area versus energy.

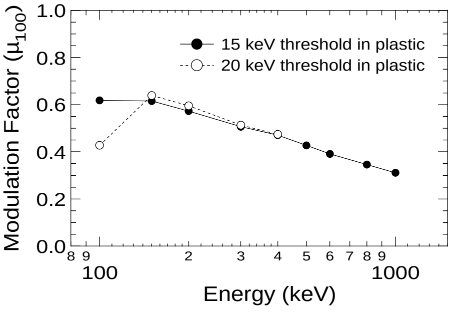

FIGURE 5. Modulation factor versus energy.

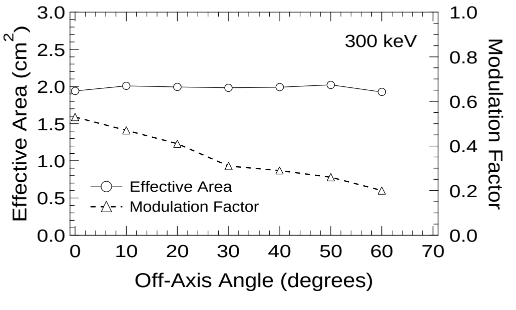

FIGURE 6. The modulation factor and effective area as a function of incidence angle for a photon energy of 300 keV.

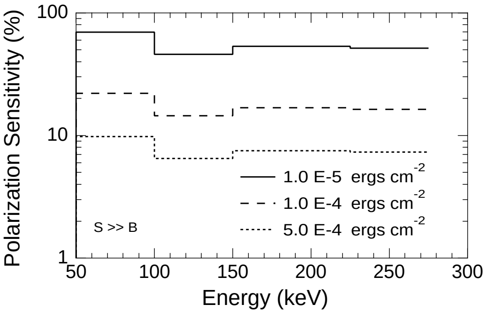

FIGURE 7. The 3σ sensitivity level of a 16-module array to γ-ray bursts. Fluence levels are for the 50–300 keV range.

The use of polarimetry in X-ray and γ-ray astronomy has so far been largely limited to energies below 100 keV [5–7,2,8], with an emphasis on the study of non-transient sources. Several higher energy experiments offer polarimetry as a secondary capability [9,10]. Although designs similar to that proposed here have been discussed in the literature [6,11], we are unaware of any other *active* effort to specifically measure polarization in γ-ray bursts at energies above 100 keV.

ACKOWLEDGEMENT

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