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Gamma ray polarimetry using a position sensitive germanium detector

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Imaging gamma-ray detectors make sensitive polarimeters in the Compton energy regime by measuring the scatter direction of gamma-rays. The principle is to capitalize on the angular dependence of the Compton scattering cross section to polarized gamma rays and measure the distribution of scatter directions within the detector. This technique is effective in a double-sided germanium detector between roughly 50 keV and 1 MeV. This paper reviews device characteristics important to the optimization of a Compton polarimeter, and summarizes measurements we have made using a device with a 5×5 cm active area, 1 cm thickness, and strip-electrodes on a 2 mm pitch.

1. Introduction

Gamma-ray polarimetry in the Compton energy band is interesting in nuclear decay measurements, and in high energy astrophysics where observations have not been possible with the technologies employed in current and past space missions. Polarization is expected from Compton reflection in a variety of sources such as off accretion disks or jets around black holes [1], or off the photosphere in a solar flare [2]. Polarization should also be observed from cyclotron absorption and synchrotron radiation near highly magnetized objects such as pulsars [3], or from regions of intense gravitation fields [4] and gamma ray bursts.

Two-dimensional germanium strip detectors (GSD) are semiconducting devices with electrodes on opposite faces to measure both energy and position of each interaction. GSDs have been demonstrated to provide the excellent energy resolution typical of a germanium detector with good imaging capability [5]. Spatial resolution is defined to be the closest that two interactions can be to each other and still be resolved. Spatial resolution is potentially ~200 microns in a 1 cm thick device, limited by the lateral diffusion of the charge cloud following an interaction [6], and by the strip pitch of the electrodes.

The large volume of a germanium detector compared with other solid-state detectors is important to achieve reasonable detection efficiency of polarization events. The detection requires that the gamma ray first be Compton scattered, followed by a total energy absorption. Ideally the total energy absorption is a photoelectric interaction, or is contained entirely within a single imaging pixel in the detector. Thus, the best polarization events have a signature of energy loss in exactly two imaging pixels within the detector. In principle, events with three or more interactions may be utilized, but the process is more complicated and is beyond the scope of this work. The distribution of scatter directions forms the basis of the polarization measurement.

The advantage of the GSD as a polarimeter is that every imaging pixel serves as both a scatterer, and as an absorber. Thus, the full area of the detector is useable to scatter the incoming gamma rays, and the scattered gamma ray has the entire volume of the detector for the second interaction. Good energy resolution, characteristic of a germanium detector, is also important to select events with a high modulation fraction.

2. Principles

A linearly polarized gamma ray will preferentially scatter in a direction perpendicular to the direction of polarization. It is therefore possible to design a polarimeter to measure the distribution of scatter directions [7,9,10], and thus deduce the degree of polarization of a source. We choose a coordinate system with the direction of a gamma-ray beam along the z-axis, and the direction of polarization along the x-axis. In this system, the Compton scatter angle, θ, is the angle of the scattered gamma-ray from the z-axis, and the azimuthal angle, ϕ, is measured between the scattered gamma-ray and the x-axis in the x-y plane. An unpolarized beam will have a uniform distribution of scatter directions in ϕ The differential Compton scattering cross section for a polarized beam is given by:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \beta^2 \left[\beta + \beta^{-1} - 2\sin^2\theta\cos^2\phi\right] \qquad (1)$$

where r_e is the classical electron radius, and β is the ratio of scattered to incident photon energy.

Polarization is detected by the difference in gamma rays that scatter in one direction vs. the perpendicular direction. The function used to find the maximum scatter direction is the modulation ratio defined by,

$$R(\phi) = \frac{N(\phi+90) - N(\phi)}{N(\phi+90) + N(\phi)} = \frac{\sigma_\perp - \sigma_{//}}{\sigma_\perp + \sigma_{//}} \qquad (2)$$

where ϕ is the azimuth angle. Modulation fraction is expressed in normalized units for comparison with the scattering cross sections. R is maximum when ϕ is in the direction of the initial polarization vector, and minimum when they are perpendicular.

The modulation fraction as a function of Compton scattering angle is shown in Figure 1. Lower energies have a higher modulation fraction. The maximum modulation fraction is over 90% for energies below 200 keV, and occurs for events that Compton scatter by ~90°. The peak of the curve moves to slightly smaller angles with increasing energy which may be useful in designing detectors that are optimized above ~1 MeV. The modulation fraction diminishes to zero for small angle scattering, and for backscattering. Thus the most useful events are those that scatter in limited band of angles around 90°. The detection efficiency is shown in Figure 2, expressed as the fraction of gamma rays that are useable for polarimetry. Events are selected which have exactly two interactions in the GSD (K shell fluorescence is not counted as a third interaction for this purpose). The curves are determined by a simple Monte Carlo program and are for total energy absorption. The efficiency increases in a crudely linear fashion with the width of the angular range of Compton scatters. The band 90°±30° is a good compromise between maximization of the modulation fraction (Figure 1), and reasonable efficiency.

The Compton scatter angle is determined in a detector with good energy resolution by measuring the energy of both interactions and applying the Compton scattering formula. The energy loss in the first and second interactions as a function of incident energy is shown in Figure 3. The curves indicate the band of Compton scatter angles between 60° and 120° that are considered for polarization measurements. For energies below ~340 keV, the first interaction is always the smaller of the two in this range of scatter angles. Knowledge of which interaction was first is not critical however, unless the detector is also being used for imaging. A 4.2 keV threshold is the smallest signal that can be measured using our laboratory GSD.

Good spatial resolution improves the efficiency and the azimuthal resolution the polarimeter. The efficiency of the 1 cm thick GSD is shown in Figure 4 for two different strip pitches. In a realistic device, we have found that events in adjacent imaging pixels have serious systematic biases in measuring scattering directions. This results from a combination of effects from charge sharing between strips due to the range of the recoil electrons, lateral diffusion of the charge cloud, different properties of the strips on the opposite faces of the detector, and the gross geometry factor between adjacent pixels. Rather than calibrate these effects, it has been easier to demand that there is at least one strip with no signal between the strips where energy loss has been detected. This ensures a modest separation between the two events, and reduces systematic effects to very low levels. This also reduces the detector efficiency if the strips are very wide, particularly at lower energies as can be seen in the Figure. The narrower 0.5 mm pitch strips approach the theoretical maximum efficiency everywhere above ~100 keV, and provide better than 1% efficiency down to 60 keV. The 2 mm pitch GSD requires the scattered gamma ray to travel at least 2 mm through germanium in order to be selected as good events, thus the efficiency is substantially less.

3. Measurements

We have measured performance of a 1 cm thick GSD with 2 mm strip pitch at 100 keV and 290 keV. These results have been previously reported [7,8]. We achieved a polarized beam by scattering 122 keV and 662 keV gamma rays respectively by 90 degrees in a small plastic scintillator. The plastic scintillator was used in coincidence with the GSD to eliminate background events.

The polarization measurements are shown in Figures 5 and 6. There is no special calibration required to make these measurements. These figures are the raw distribution of scatter directions in the detectors, selected by scatter angles in the range from 60° to 120°. The scatter directions are divided into four quadrants for summing using equation 2 (0°, 30°, 45°, and 60° with respect to the detector axes). The data are plotted on a full 180° cycle simply for display. The points at 0°, 90°, and 180° are identical data except for a sign. The modulation factor, *i.e.* the sensitivity of the polarimeter defined by equation (2) ranges from 0 (no sensitivity) to 1 (ideal). It is measured for the GSD with 2 mm strip pitch by the amplitudes in Figures 5 and 6, divided by the degree of polarization of the test beam. The results are 0.62 and 0.60 at 100 keV and 290 keV respectively. This should be compared with 0.82 and 0.71, which should be theoretically possible using data in the 60° to 120° scatter range. A large portion of the difference between measurement and theory is attributable to the geometry factor of nearby pixels adding error in the azimuth angle determination. A higher modulation factor should be achieved with finer pitched electrodes. These results compare favorably to polarimeters based on scintillators which depend on geometry to select the Compton scatter angle [9,10].

4. Discussion

The Compton scatter angle of the gamma ray is not determined geometrically in the GSD, but rather by directly measuring the energy loss in each pixel. This process has been referred to as "kinematic data selection" or "electronic collimation". The alternative of geometric selection of good events has the drawback of reducing efficiency of the detector. Failing to select for optimum scatter angles has the effect of mixing events with low modulation, thus reducing sensitivity. Thus a fully active detector is the ideal device, maximizing both efficiency and selection of optimum scatter angles.

Alternative semiconductors should also work as polarimeters. The best performance is achieved on or about the energy that the photoelectric cross section and Compton cross sections are equal. For germanium this is 150 keV. For CdZnTe, this is 260 keV. Thus, large volume CdZnTe detectors may have efficiency advantages at higher energies where they have better stopping power. However, the photoelectric absorption in CdZnTe will limit its use below ~200 keV. Silicon may also be used at lower energies. Ultimately, silicon is limited by the requirement of measuring very small energy losses of the first scattering. Thus, a silicon design might emphasize larger scatters on the order of ~120° and use a secondary detector (Ge or CdZnTe) to capture the scattered energy.

A space instrument designed to study polarization of sources such as the Crab nebula and pulsar is possible. In earlier work, we report on an instrument concept called GIPSI [7] consisting of 16 GSDs that could detect a minimum degree of polarization of 1.5% in the Crab nebula and 5.2% in the pulsar in the 70–300 keV band with a 2 week observation. This prediction was based on GSDs with a 2 mm electrode pitch. Based on this work, a factor of ~2 improvement is possible using GSDs with a 0.5 mm electrode pitch.

References

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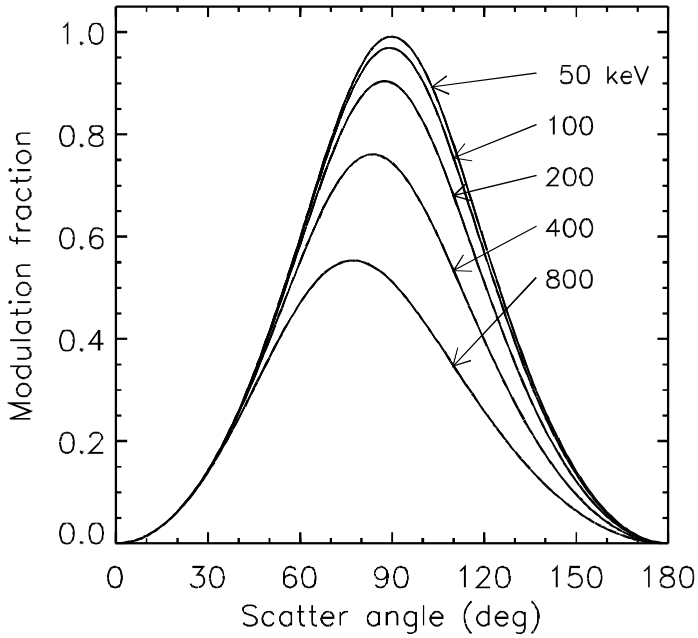

FIGURE 1: **Modulation fraction for various energies as a function of Compton scatter angle θ.**

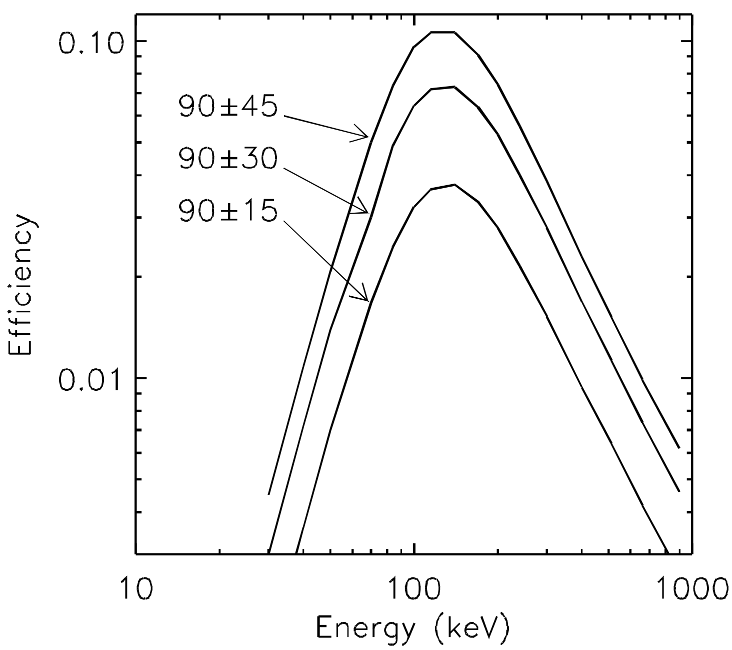

FIGURE 2: **Maximum detection efficiency selecting for events by the Compton scatter angle.**

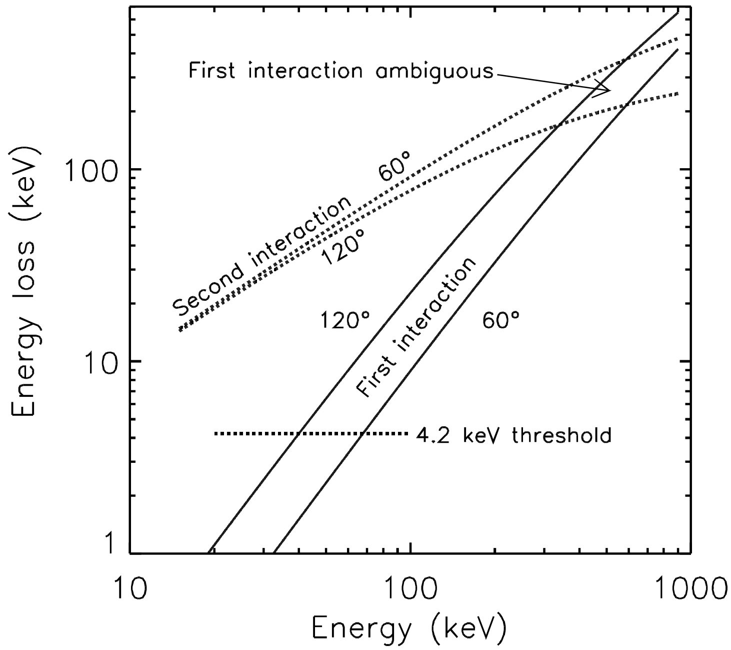

FIGURE 3: **Energy loss in the first and second interactions.**

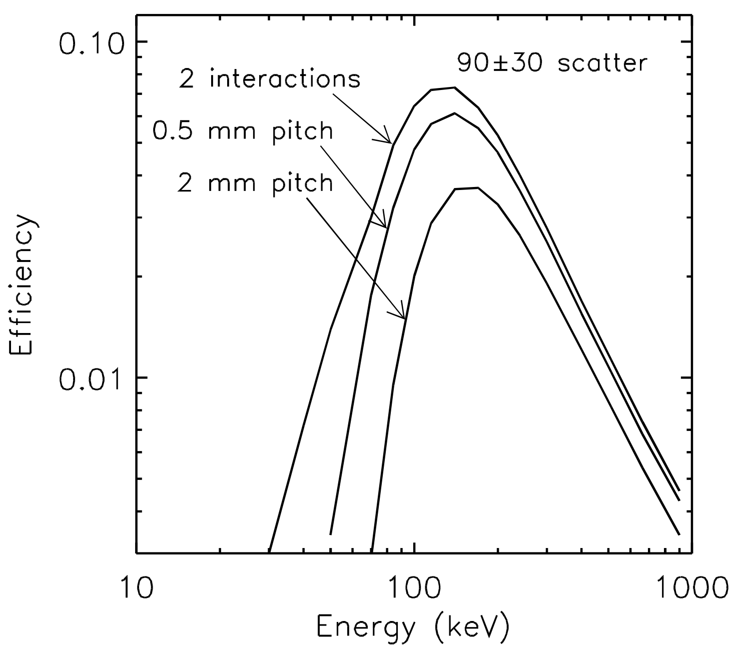

FIGURE 4: **Detection efficiency for a GSD with 0.5 mm and 2 mm strip pitch, compared with the maximum achievable efficiency.**

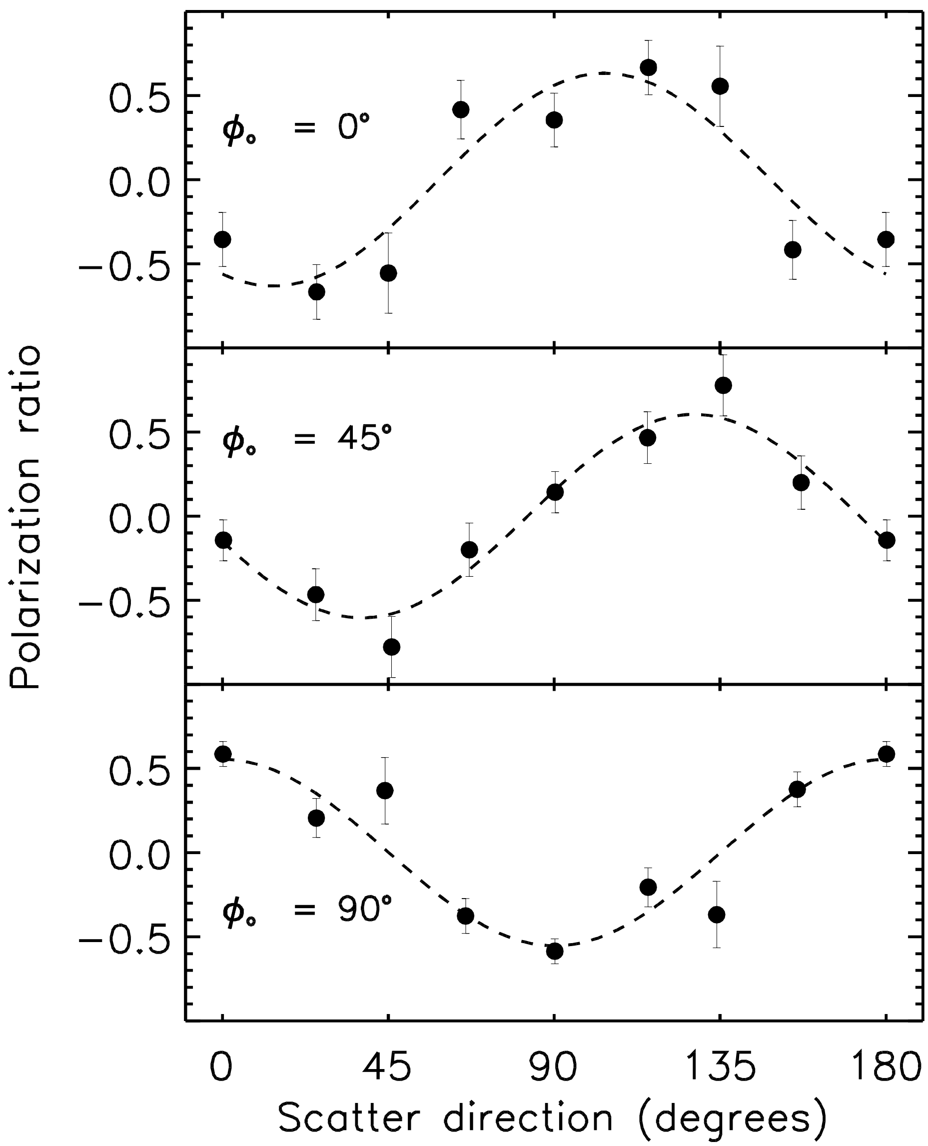

FIGURE 5: **Polarization ratio measured at 100 keV with a 97% polarized beam. The direction of beam polarization is ϕ_0. The minimum in the curve is the measured polarization direction, and the amplitude is proportional to the degree of polarization.**

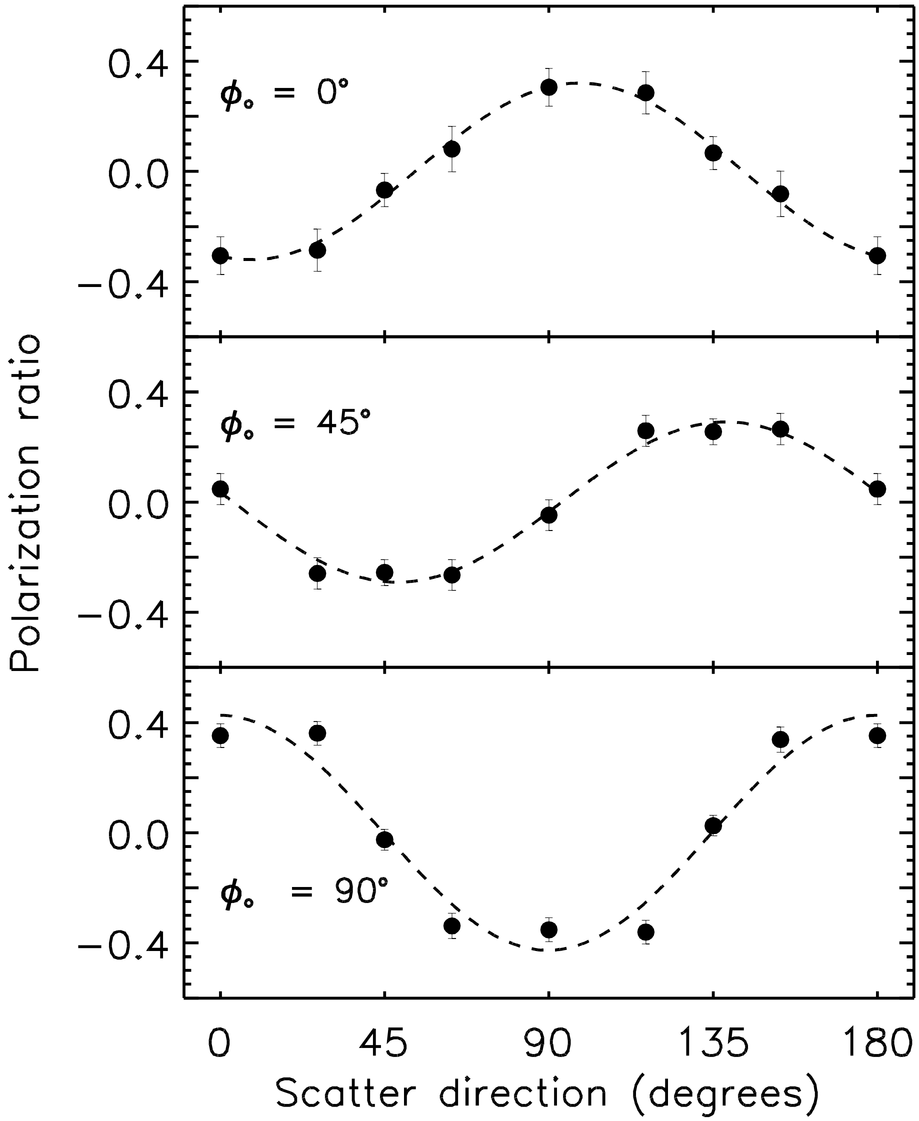

FIGURE 6: **Polarization ratio measured at 290 keV with a 60% polarized beam.**