EXPERIMENTAL RESULTS OBTAINED WITH THE POSITRON- ANNIHILATION-RADIATION TELESCOPE OF THE TOULOUSE-ARGONNE COLLABORATION

J. E. Naya[1], P. von Ballmoos[1], R. K. Smither[2], M. Faiz[2],
P. B. Fernandez[2], T. Graber[2], F. Albernhe[1], G. Vedrenne[1]

[1]*Centre d'Etude Spatial des Rayonnements, 9, Av. du Colonel Roche, 31029 Toulouse, France*
[2]*Advanced Photon Source, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439 USA*

Abstract. We present laboratory measurements obtained with a ground-based prototype of the focusing positron-annihilation-radiation telescope developed by the Toulouse-Argonne collaboration. This instrument has been designed to collect 511-keV photons from astrophysical sources when operating as a balloon borne observatory.
The ground-based prototype consists of a crystal lens holding small cubes of diffracting germanium crystals and a 3x3 germanium array that detects the concentrated beam in the focal plane. Measured performances of the instrument at different line energies (511 keV and 662 keV) are presented and compared with Monte-Carlo simulations; also the advantages of combining the lens with a detector array are discussed.
The results obtained in the laboratory have strengthened interest in a crystal-diffraction telescope : The balloon instrument will provide a combination of high spatial and energy resolution (15 arc sec and 2 keV, respectively) with an extremely low instrumental background resulting in a sensitivity of ~3×10^{-5} photons $cm^{-2}s^{-1}$. These features will allow us to resolve a possible narrow 511-keV line both energetically and spatially within a Galactic center "microquasar" or in other broad-class annihilators.

1. Introduction

Recently, the Toulouse-Argonne collaboration presented a focusing gamma-ray telescope that may begin a new era in gamma-ray astronomy. This instrument, designed to collect 511-keV photons with an extremely low instrumental background, consists of a Laue diffraction lens; a detector module with a 3x3 germanium array; and a balloon gondola stabilized to 5" pointing accuracy. The instrument has been described by von Ballmoos and Smither in ref [1].

As a first step in the project schedule, a ground-based prototype telescope has been built. It consists of a diffraction lens focusing at finite distances (provided by ANL, Chicago) and a 3x3 Ge array detector (provided by the CESR, Toulouse).

In this paper, we present a part of the experiments conducted and the measured performance of the system. The results obtained validate the concept of a gamma-ray telescope using a diffraction-lens and open interesting perspectives for the development of the balloon-telescope model.

2. System test at Argonne

The test was performed at Argonne National Laboratory in June/July 1994. Our experimental setup used can be divided into three parts: the source, the lens module, and the detector module.

A characteristic of the ground-based lens is the possibility of focusing a wide range of energies without retuning the lens. To accomplish this, one adjusts the distance from the source to the lens (D_S) and the distance from the lens to the detector (D_D) to match the corresponding Bragg diffraction angle. For small diffraction angles, the relationship between D_S and D_D is the same as for a thin convex lens :

$$\frac{1}{D_S} + \frac{1}{D_D} = \frac{1}{F}, \quad 1)$$

where F is the focal length of the lens for a given gamma-ray energy. A general view of the experimental setup is shown in figure 1.

The Source

The high-energy gamma-ray sources used in these experiments are characterized in table 1. They are enclosed in a massive lead shield and are well collimated into a narrow cone of radiation just large enough to illuminate the lens. In this work, we present in detail the results for the 511-keV line, which represents the energy of interest for the proposed astrophysical telescope.

Lens module

A schematic front view of the crystal diffraction lens is shown in Figure 2 : up to 600 Ge crystals cut into small cubes of dimension 1 cm x 1 cm x 1 cm are mounted onto a stainless steel frame in eight concentric rings (indicated by dark shaded areas). To compensate for the change in diffraction angle, each ring contains crystals cut so that a different set of crystalline planes is used for diffraction. The radius of each ring is designed such that each crystal in a ring focuses the same energy gamma-ray into a small focal spot simultaneously.

The results presented in this article were obtained with a prototype lens containing 416 Ge crystals in six rings.

Due to the finite distance between the source and the lens, only a small percentage of the gamma-ray flux incident on the face of an individual crystal will have the correct Bragg angle and be diffracted. However, to optimize the diffraction efficiency of the crystals, they are divided in three parts by two wedged slots. This partly compensates for the change in the angle of incidence of the photons impinging on the crystals front surface.

The finite size of the source (3-mm diameter) produces a larger focal spot than would be expected for a point source (2.0-cm diameter instead of 1.7 cm for an ideal point source). For several of the experiments performed, we required a focal spot size smaller than the pixel surface, so a collimator consisting of a lead brick (10 cm thick) with a cylindrical hole (8-mm diameter) was used.

The angular position of the lens axis is monitored using a laser beam reflected off a mirror mounted on the central axis of the lens. The 15-m-long lever arm of the laser beam allows the absolute angular position of the lens to be monitored to within a few arc seconds.

Detector module

A novel gamma-ray detector consisting of a high-purity 3x3 germanium matrix housed in a single cylindrical aluminum cryostat was used for these experiments. Each of the single Ge bars is an n-type coaxial detector with dimensions of 1.5 cm x 1.5 cm x 4 cm and an

internal electrode hole of 4-mm diameter. The distance between the front surface and the electrode hole is 1 cm.
The thermal control for the detectors is provided by a liquid-nitrogen dewar with a capacity of 30 l. The bias voltage is of -700 V. Electrical connections between the Ge crystals, the detector preamplifiers and bias supply are made via feed-thru's welded into the rear wall of the cryostat. Each detector is de-coupled to the preamplifier input (FET) stage. The FETs and the last stages of bias filtration and decoupling are housed in a cylindrical box attached to the rear wall of the cryostat. The electronics and data processing systems consist of a high voltage, 9 amplifiers, 5 peak detectors, an analog-to-digital converter (ADC) housed in NIM bins. A PC 8086 with a communication card handles the connection with the electronic set-up.

Gamma-ray interactions in the array are processed and transmitted on an event-by-event basis. When an interaction is produced in one of the crystals of the array depositing an energy greater than the electronic threshold (40 keV), a "photon detection" signal is transmitted to the PC. At this time, the computer starts a dialog with the electronics to process the event. The transmitted information consists of a series of words containing:

1) the event multiplicity (i.e., the number of crystals that have received a simultaneous energy deposit) and the identification of the triggered detectors;

2) the pulse-height channel numbers, two bytes for each triggered detector.

The data are recorded in their raw form on the hard disk for later spectral analysis. The data acquisition software also provides facilities to calibrate the detectors and create spectra from the raw data file. In order to generate any desired spectrum, a menu allows one to easily choose any possible combination of detectors and multiplicities.

3. Experiment results

3.1 Lens efficiency

The efficiency of the lens for diffracting 511-keV photons is given by the formula:

$$\varepsilon_{diff} = \frac{A_D \cdot N_L \cdot D_S^2 \cdot \varepsilon_{nc}}{n \cdot s \cdot N_D \cdot (D_I + D_S)^2 \cdot \varepsilon_c}, \qquad (2)$$

where N_L is the count rate of 511-keV events diffracted by the lens and seen by the detector; N_D is the count rate measured by the detector when the lens is removed from the system; D_S is the distance from the lens to the source; D_I is the distance from the lens to the detector; A_D is the area of the detector; n is the number of diffracting crystals in the lens; s is the average surface area of the front side of a single crystal, ε_{nc} is the detector efficiency for a non concentrated beam; and ε_c is the detector efficiency for a concentrated beam.

In order to calculate the lens efficiency, the intensity of the diffracted beam was measured with a modified Ortec HPGe detector system, normally used at ANL, instead of the array because of its less complex geometry. The ANL detector consists of an n-type coaxial germanium detector, 6 cm in diameter and 6 cm high. The diameter of the inner hole is 1 cm, and the distance from the front surface to the reentry hole has been customized to 3 cm. This modification makes the ANL detector more efficient at these energies than standard Ge detectors, which have a distance of 1 to 1.5 cm between the front face and the reentry hole. The photo-peak efficiency for this detector is 31 % when the entire surface of the detector is illuminated (non-focused beam). When the beam is focused, the photo-peak efficiency increases. Since the gamma-ray beam is confined to a smaller volume within the detector, the Compton-scattered photons have a higher probability of being detected because they are not created near the sides of the detector where a part of the photon energy could be lost. This results in a photo-peak efficiency of 48% for the focused beam.

In order to calculate the lens efficiency at 511 keV, the total counting rate of the source-lens-detector system was measured. To eliminate transmission of the non-diffracted beam through the lens and into the detector, the center of the lens was blocked. After background subtraction, we found N_L = 153 c s^{-1} (count rate in the peak) with the lens

tuned. Next, the lens was removed from the system, and the measurement was repeated. The count rate without the lens was N_D = 77 c s^{-1} (in the peak).
After substitution of the parameters in formula (2), we find that the diffraction efficiency for 511-keV photons is 2.8%, corresponding to an effective diffraction surface of 17 cm^2.

The low efficiency in this case is due to the narrow intrinsic rocking curve (~2 arc sec FWHM) of the crystals used in the present lens. The Na source, as seen by a single lens crystal, subtends an angle of about 25 arc sec. Yet, because of its relatively narrow rocking curve, a typical crystal can only diffract photons that are emitted from a small 2 arc sec strip of the source. Techniques for increasing the width of a germanium crystal's rocking curve are being developed and will be incorporated in future lens prototypes. However, it should be noted, that the efficiency of the present lens would increase significantly for a source at infinity. For an astrophysical source with an angular radius on the order of 2 arc sec or less, the efficiency of present lens could be as much as 22% at 511 keV

3.2 Ge array efficiency

The efficiency calculations for the Ge array were carried out by comparing the measured count rates of the detector array with the count rate observed for the ANL detector. The ratio between their count rates must be equal to the ratio between their efficiencies.

The measured efficiencies for a 511-keV gamma-ray beam incident on a 0.8-cm- diameter focal spot are shown in table 2. We used the collimator described in the above section to limit the focal spot size to less than the pixel surface, which is representative for the case of a source at infinity. The different focal spot positions referred to in the table are represented in fig 3. We have calculated the photopeak efficiencies for an equivalent geometric setup by Monte-Carlo simulations based upon CERN's GEANT [2]. The results are displayed in table 2. Single and multiple events are determined by photon detection occurring in one or various pixels respectively.

3.3 Background reduction

The segmentation of the 3x3 Ge matrix together with the concentrated beam from the crystal lens allows application of new techniques for background reduction. The method consists of only accepting events that are compatible with the signature of a "good" 511-keV photon coming from the crystal lens. In other words, when the focal point of the lens is centered on one pixel of the array, 511-keV photons that deposit any energy in that pixel are considered as "good" events. We can see in table 2 that the measured percentages of background rejection from an isotropic ambient background flux are associated with different positions of the focal spot. The rejection of 79.3 % in the position I represents an improvement in the sensitivity by a factor of 2.2 in comparison with a standard detector of the same volume.

3.4 Off axis source recognition

The germanium detector array allows us to take maximum advantage of a focused gamma-ray beam to spatially resolve the source. The focal spot can be easily localized looking at the 9 count rates. This also allows imaging of an off-axis source. Fig. 4 shows a series of measurements in which the source-lens-detector system has been intentionally misaligned. The gamma-ray energy in this experiment was 662 keV. In the first drawing, the alignment is perfect, the focal spot being on the central pixel. The next three drawings show measurements with the lens shifted along the Y-axis 5 mm, 7.5 mm, and 10 mm, respectively. One can observe the movement of the focal spot as well as the decrease in the intensity of the focused beam due to the loses of diffraction efficiency because of the misalignment. Finally, the last drawing shows a measurement when the required tilt was applied to the lens in order to match the Bragg condition with a shift of 10 mm. The focal spot is on detector 4, but the initial intensity of the diffracted beam has been recovered.

4. Discussion

The results of the tests validate the lens-telescope concept: the lens diffracts the gamma rays concentrating them into a small focal spot on the detector surface. Because the signal is associated with the collection surface and the background is associated with the detection volume, the large lens collection area combined with the small Ge array volume makes an optimal instrument for maximizing the signal-to-noise ratio. Our system consisting of a Ge diffraction lens and a Ge detector array provides the following advantages:

1 The possibility of background rejection (up to 80%) combined with a maximum detection efficiency. With the focal spot placed far from the array borders, the efficiency increase is 25% over the nonfocused beam efficiency at 511 keV.

2 Off-axis source recognition.

3 The possibility of simultaneous background monitoring. The fact that the signal is localized within a small volume of the matrix can be used to define equivalent volumes within other detector pixels that are not receiving signal photons. In this equivalent volume the background count rate can be measured simultaneously to the source observation.

The extrapolation of these results to a balloon diffraction-lens telescope consisting of a 600-crystal lens, working at 511 keV, combined with the presented detector array results in an instrument with performances shown in table 3. The focusing by the lens results in a gain of the signal-to-noise ratio of about 20 with respect to an identical simple Ge detector.

Such an instrument would be able to resolve, both energetically and spatially, compact sources emitting narrow 511-keV photons. Interesting candidates to observe would be the "microquasars" at the Galactic center [3], such as 1E 1740.7-258 [4] or GRS 1758-258 [5], as well as other objectives like Cygnus X-1, X-ray binaries, and pulsars.

5. Acknowledgments

This work was partially supported by the U.S DoE Contract No. W-31-109-Eng-38, by the *Region Midi-Pyrénées* (Toulouse) and the French Space Agency (CNES).

6. References

[1] von Ballmoos, P. and Smither R. 1994, ApJ Sup. S., 92, 663
[2] GEANT CERN Program Library Office
[3] Ramaty, R., Leventhal, M., Chan, K. W., & Lingenfelter, R. 1992, ApJ, 392, L63
[4] Mirabel, I.F., et al. 1992, Nature, 358 (No. 6383), 215
[5] Rodríguez, L.F., et al. 1992, ApJ, 401, L15

Figure captions

Fig. 1 Experimental set-up of the system test at Argonne Natl. Laboratories. Different distances D_S and D_D where utilized to satisfy the Bragg condition for the photons energies E_γ=511 keV (^{22}Na), and E_γ=662 keV (^{137}Cs), respectively.

Fig. 2 Schematic front view of the lens module. The dark ring segments host the diffracting germanium crystals. The cross pattern in the central part of the frame is a coded aperture mask which can be used to verify the pointing of the instrument for sources with a hard X-ray continuum spectrum.

Fig. 3 Focal spot position for the table 2

Fig. 4 Telescope response for focusing off axis sources : The first drawing shows the system performance when the source, lens, and array are perfectly aligned. The following three drawings show the evolution of the focal spot position as well as the diffraction efficiency when the lens is displaced along the Y axis. The last drawing shows a measurement for a displaced lens (10 mm) which is tilted such that it is aligned with the source; this way, the focal spot is on detector 4 and the initial efficiency of the system is recovered.

Tables

Source	Energy [keV]	Activity [mCu]	Focal length [m]	D_S [m]	D_i [m]
^{137}Cs	662	180	10.92	24.75	19.54
^{22}Na	511	50	8.43	19.11	15.09
^{239}Pu	375		6.83	15.47	12.22

Table 1: *Description of the used gamma-ray sources*

	Monte-Carlo calculation		Measured		
Position	**SINGLE events eff.[%]**	**MULTI events eff. [%]**	**SINGLE events eff.[%]**	**MULTI events eff. [%]**	**Background rejection [%]**
I	12.0	14.9	12.7	12.4	79.3
II	12.9	18.6	16.4	16.6	66.3
III	12.1	10.8	12.9	8.3	83.4
IV	10.8	19.2	11.1	14.6	44.9
V	12.1	7.7	11.4	6.1	85.1

Table 2: *Measured and Monte-Carlo efficiencies for 511-keV photons incident on various focal spot positions on the 3x3 array. The fourth column shows the measured background rejection for each of the focal positions.*

Telescope Performances	
Lens surface	600 crystals 1 cm^2
Diffraction efficiency	25 %
Angular resolution	15 "
Energy resolution	2 keV at 511 keV
Detector efficiency	30 %
Background rejection	80 %
3 σ sensitivity	3 10^{-5} photons cm^{-2} s^{-1} *

* For a 20 hours observation mission in Alice Springs, Australia

Table 3: *Performances of the proposed balloon telescope. They have been extrapolated from the ground-based telescope measurements.*