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

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Abstract. We present laboratory measurements obtained with a ground-based prototype of a focusing positron-annihilation-radiation telescope developed by the Toulouse-Argonne collaboration. This balloon-borne telescope has been designed to collect 511-keV photons with an extremely low instrumental background. The telescope features a Laue diffraction lens and a detector module containing a small array of germanium detectors. It will provide a combination of high spatial and energy resolution (15 arc sec and 2 keV, respectively) with a sensitivity of ~$3x10^{-5}$ 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.

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. The advantages of a 3x3 Ge-detector array with respect to a standard-monoblock detector have been confirmed.

The results obtained in the laboratory have strengthened interest in a crystal-diffraction telescope, offering new perspectives for the future of experimental gamma-ray astronomy.

1. Introduction

Recently, the Toulouse-Argonne collaboration presented a new type of gamma-ray telescope that may begin a new stage 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 [1].

As a first step in the project schedule, a ground-based prototype telescope has been achieved. 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 some of the experiments achieved and the measured performance of the system. The results obtained validate the diffraction-lens-based telescope concept 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. It 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_I) to match the corresponding Bragg diffraction angle. The relationship between these distances for small angles is:

$$\frac{1}{D_S} + \frac{1}{D_I} = \frac{1}{F} \quad (1)$$

where F is the focal length of the lens for a given gamma-ray energy.

2.1 THE SOURCE

The high-energy gamma-ray sources used in these experiments are described in table 1. They are enclosed in a large 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 from the 511-keV line, which represents the energy of interest for the proposed telescope.

Source	**Energy [keV]**	**Activity [mCu]**	**Focal l. [m]**	**D_s [m]**	**D_i [m]**
^{137}Cs	662	100	10.75	24.75	19.00
^{22}Na	511	39	8.30	18.48	15.07

Table 1: A description of the gamma-ray sources used in this experiment is presented. Focal l. is the focal length of the lens for the considered energy; Ds is the distance between the source and the lens; and Di is the distance between the lens and the projected image (where the detector is placed.)

2.2 LENS MODULE

The lens used in these experiments consists of 416 Ge crystals cut into small cubes of dimension 1 cm x 1cm x 1cm. These cubes are mounted in six concentric rings on a stainless steel frame. To compensate for the change in 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.

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 compensates for the change in the angle of the gamma rays as they impinge upon the front surface of the crystal.

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.

2.3 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. Two adjacent elements are separated by 2 mm with an indium surface of 0.5 cm^2.

3. Experiment results

3.1 LENS EFFICIENCY

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

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

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 lens 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 detector more efficient at these energies than the standard model, which has 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 in this case have a higher probability of being detected since they are not created near the sides of the detector. This results in a focused photo-peak efficiency of 48%.

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%, which corresponds 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. 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. A technique for increasing the width of a germanium crystal's rocking curve has been developed and will be incorporated in any future lens. However, it should be noted that, if the source subtended a smaller angle, the efficiency of the present lens would increase significantly. 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%.

3.2 Ge ARRAY EFFICIENCY

The efficiency calculations 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 were of 25% when the focal spot is placed on the central pixel and 18% when it is placed on the pixel of the corner.

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 some energy in that pixel are considered as "good" events. The measured background rejection from an isotropic ambient background flux is 79.3% when the focals spot is on one pixel. This 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. 1 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.

The germanium-array-lens system also 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 source monitoring. The fact that the signal is localized to a small volume can be exploited by defining equivalent volumes within other detector pixels that are not receiving signal photons. This allows the use of these equivalent volumes to monitor the background; thus, eliminating the problem of background fluctuations during observations.

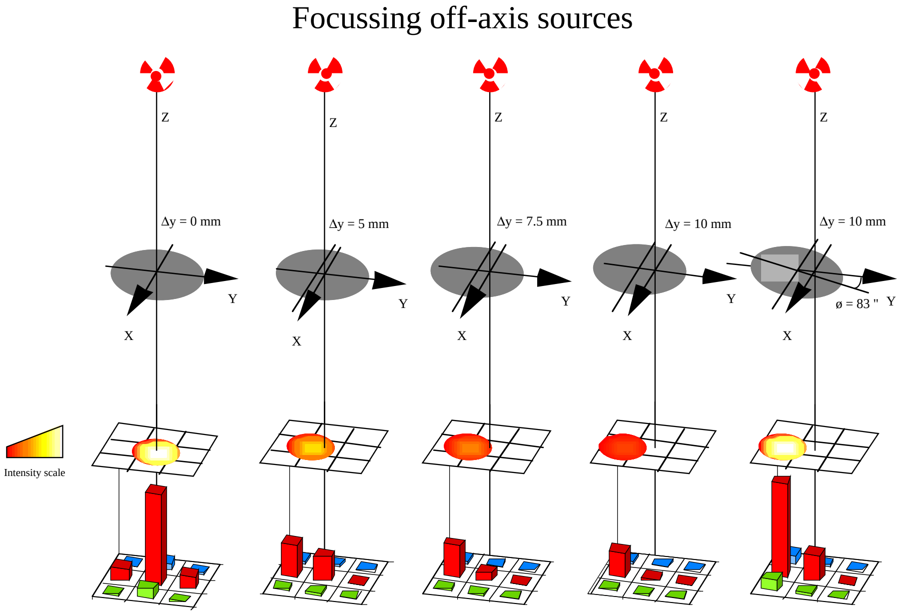

Fig. 1: The telescope response for focusing off axis sources is shown.

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 a FOV of 10"-20", an energy band of 6 keV at 511 keV, and a spatial resolution of 15" FWHM. The 3 σ sensitivity for a 20 hr balloon flight mission in Alice Springs would be 3x10^{-5} photons cm^{-2} s^{-1}. Such an instrument would be able to resolve, both energetically and spatially, point 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.

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