Design and flight performance of a crystal diffraction telescope

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ABSTRACT

We present the design and performance of the gamma-ray lens telescope CLAIRE, which flew on a stratospheric balloon on June 14, 2001. The objective of this project is to validate the concept of a Laue diffraction lens for nuclear astrophysics. Instruments of this type, benefiting from the dramatic improvement of the signal/noise ratio brought about by focusing, will combine unprecedented sensitivities with high angular resolution.

CLAIRE's lens consists of Ge-Si mosaic crystals, focusing gamma-ray photons from its 505 cm^2 area onto a small solid state detector, with only 7.2 cm^3 volume for background noise. The diffracted energy of 170 keV results in a focal length of 279 cm, yet the entire payload weighed under 500 kg.

CLAIRE was launched by the French Space Agency (CNES) from its balloon base at Gap in the French Alps (Southeast of France) and was recovered near Bordeaux in the Southwest of France after roughly 5 hours at float altitude.

After presenting the principle of a diffraction lens, the CLAIRE 2001 flight is analyzed in terms of pointing accuracy, background noise and diffraction efficiency of the lens.

Keywords: Stratospheric Flights,Gamma Ray Spectroscopy, Instrumentation for Nuclear Astrophysics, Crystal Diffraction

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1. INTRODUCTION

Present telescopes for high energy astrophysics (from about 100 keV up to several MeV) make use of geometrical optics (shadowcasting) or quantum optics (Compton scattering). The main problem of these systems is that the collecting area is smaller or equal to the detecting area. Thus, the larger the collecting area, the higher the instrumental background, and, as a consequence, nuclear astrophysics has reached something of a dead end where bigger is not necessarily better.

2. DESCRIPTION OF THE LENS

One possible way to overcome this obstacle consists of focusing γ-rays from a large collecting area onto a small detector, exactly as it is usually done with less energetic photons. If this can be done, the background noise can be extremely low, making unprecedented sensitivities possible. Yet, due to the high energy of γ-ray photons, they are usually either absorbed or incoherently scattered when interacting with matter - focusing has been considered impossible for a long time.

Nevertheless, γ-rays interact coherently inside a crystal lattice, provided that the angles of the incident photons are very small. This has led us to developing a lens using Bragg diffraction. The small angles of scattered photons and the high power of penetration of gamma rays in matter led us to choose the so-called Laue geometry. This means that photons propagate through the entire crystal, using all the crystal thickness for diffraction. In order to be diffracted, an incoming γ-ray must satisfy the Bragg relation :

$$2d\sin(\theta) = n\lambda \tag{1}$$

where d is the crystal plane spacing, θ the incident angle of the photon with respect to the crystal planes, n the reflection order, and λ the wavelength of the γ-ray. Based on this principle, the first γ-ray lens for astrophysics has been built by mounting germanium-silicon crystals in concentric rings (see Fig.1). The radius, R, of each

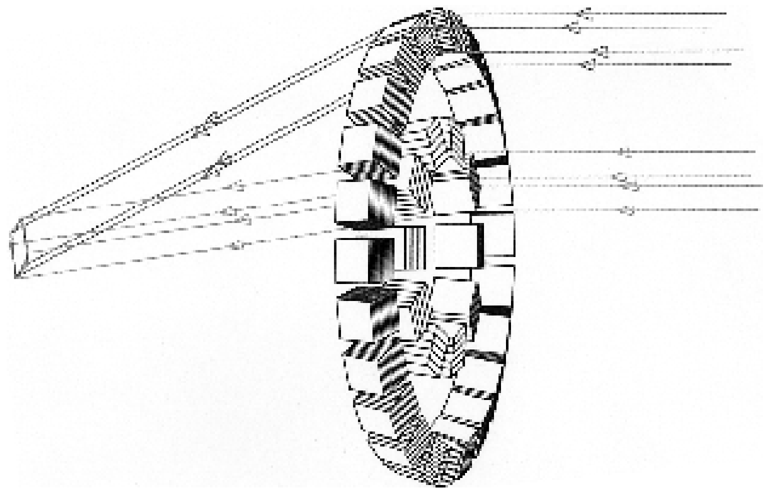

Figure 1. The principle of the gamma-ray lens

ring is given by the relationship :

$$R = D\tan(2\theta) \tag{2}$$

where D is the the focal length. Using the small angle approximation and Eq. (1), this means that R is proportional to $\frac{D}{Ed}$, where E is the energy of incident γ-rays. Thus each crystal has to be tuned i.e. oriented in order to obtain the correct scattering angle θ so that for a source at infinity all incident photons of a chosen energy are focused on the same focal point. By differentiating the Bragg relation (Eq. (1)), the energy band of a γ-ray lens is seen to be proportional to the square of the diffracted energy :

$$\Delta E \approx \frac{2dE^2\Delta\theta}{hc} \Leftrightarrow \Delta E \approx 40.0 \left(\frac{d}{d_{Ge[111]}}\right) \left(\frac{E}{511keV}\right)^2 \left(\frac{\Delta\theta}{1arcmin}\right)\ keV \tag{3}$$

where $\Delta\theta$ is the *mosaic width* of the crystal, i.e. the angular range over which the crystal reflects monochromatic radiation; $\Delta\theta$ is also characterizing the field of view of the lens.

Consequently, the main characteristics of optics using crystal diffraction lie in a narrow energy band (typically a few keV to a few tens of keV) and a small field-of-view (about 1 arcmin). Thus, a diffraction lens can be used for astrophysical observations where two-dimensional intensity mapping, observation of spectral lines in compact objects are required. The narrow energy bandpass of the lens is ideally matched to the study of nuclear transitions in the sites of nucleosynthesis (novae, supernovae) and e^+-e^- annihilation.

After testing the principle of a γ-ray lens (Naya et al., 1996, Ref. 1) on the ground, and measuring the diffraction efficiency of Ge crystals (Kohnle et al., 1998, Ref. 2), CLAIRE is the next logical step towards a space borne crystal lens telescope. For more information about the design and objectives of CLAIRE, please refer to Laporte et al., 2000, Ref. 3.

3. THE CLAIRE PROJECT

While the diffraction lens is dedicated to the observation of nuclear lines, a balloon test flight ironically requires observation of a continuum spectrum. The handicap of using a gamma-ray lens (optimally adapted to the observation of gamma-ray lines) to measure a continuum spectrum in a roughly 3 keV broad band is imposed by the need for a positive detection and the imperatives of a balloon mission : since no astronomical "standard candle" for gamma-ray line emission is presently known, the Crab was an obvious alternative. The diffracted energy, limited by the relatively short focal length of a prototype balloon instrument, has been fixed more or less arbitrarily to 170 keV (absence of BG lines, 511 keV is 3^{rd} harmonic).

The first two flights of CLAIRE occurred on June 15 2000 and June 14 2001. CLAIRE was launched from the CNES launch site at Gap in the French Alps (South-East of France) and landed close to the Atlantic coast (in the South-West of France) about 600 km away. For both the two flights, the launch took place in the middle of our launch window. Float altitude (respectively 40 and 41.5 km for the first and second flights) was reached after about 2.5 hours and lasted between 5 and 6 hours.

The first flight showed that the required pointing accuracy is feasible on a balloon. Yet, as might have been expected for the first flight of such a complex system, it took some time to optimize and calibrate the pointing system in flight conditions. A technical problem also prevented us from correctly pointing the Crab nebula more than about 1 hour. Given the relatively high background noise in the passively shielded detectors, no detection of the Crab nebula was possible. Nevertheless, the detector background lay within 20% of our prediction - this is at a measured level of $1.3 \cdot 10^{-3}$ cts$\cdot$cm$^{-3}\cdot$s$^{-1}\cdot$keV^{-1} at 170 keV.

Operation during the second flight appears to have been entirely nominal despite a flight duration shorter than expected (5h15 at float altitude with 3h40 of good pointing time, see Sec. 5.2).

4. THE 2001 CLAIRE TELESCOPE

The lens module, detector package, and pointing systems are integrated into a purpose designed telescope structure made of composite materials (See Fig. 2). The 3 m telescope structure, consisting of 18 carbon fibers spars and 3 honeycomb platforms only weighed 100 kg. The structure has been conceived, manufactured and tested by the University of Birmingham. The upper platform holds the lens and its fine pointing system (see Sec. 4.3). The detecting system (detector matrix, dewar, anticoincidence shield and collimator and electronics) are mounted on the lower platform (see Sec. 4.2).

Figure 2. CLAIRE during pointing tests at the launch site.

4.1. The Diffraction Lens

The lens, whose titanium frame was developed at the Argonne National Laboratory, is composed of 556 crystals mounted on a 8 rings. The germanium-silicon crystals used for the lens were grown by the Institüt für Kristallzüchtung and checked by the Institut Laue-Langevin. The footprint of the individual crystals (1x1 cm and 0.7x1 cm) results in a 1.4 cm diameter focal spot.The γ-ray lens mounted on its fine pointing system (see Sec. 4.3) is shown on the left-hand side of Fig. 3.

The γ-ray lens was tuned for a diffraction energy of 170 keV, corresponding to a 2.79 m focal length for our 45 cm diameter lens ($R(Ge_{[111]}) = 6.1$ cm, $R(Ge_{[440]}) = 20.2$ cm according to Eq. (2)). According to Eq. (3), this leads to a energy band of about 3 keV for a 50 arcsec mosaic width. Crystal tuning was performed on a 20 m long optical bench at CESR. Diffracting γ-rays from a 122 keV (slightly dependent on the ring) source situated 14 m in front of the lens is equivalent to focus 170 keV photons from infinity. An X-ray generator served as calibration source for the tuning. The continuum spectrum which reaches up to 150 keV facilitates tuning in comparison with the use of a radioactive source : instead of a “blind search” for diffraction at the accurate crystal inclination, the diffracted peak shows up promptly in the range of the continuum spectrum and has “merely” to be shifted to the adequate energy by tilting the crystal.

The lens axis is materialized by the invariant pixel on the CCD camera mounted in a rotating optical telescope in the center of the γ-ray lens. This method provides an alignment accuracy better than 10 arcsec, independent of the focal distance of the alignment telescope. The choice of the tuning energy of 122 keV

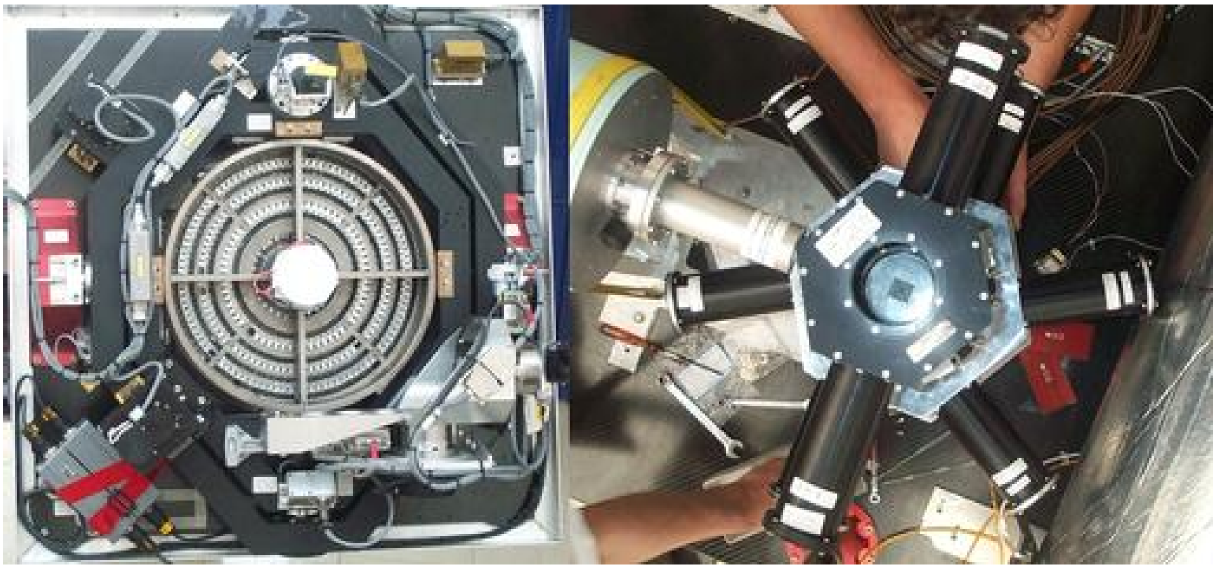

Figure 3. Left : CLAIRE's γ-ray lens (diameter 45 cm on the gimbal mount of the fine pointing system. Right : The 3x3 HP-Ge matrix surrounded by the anti-coincidence shield.

allowed us to monitor the crystal tuning with a small ^{57}Co source. According to the measures performed in the laboratory, the 505 cm^2 diffracting area corresponds to a 55 cm^2 effective area (11 % efficiency at 170 keV).

4.2. The Detector Matrix

The γ-ray detector consists of a 3x3 high purity Ge matrix. Each of the 9 elements is a 1.4 cm x 1.4 cm x 4 cm n-type coaxial detector with an central hole of 0.5 cm diameter x 3.5 cm deep (detector volume : 7.15 cm^3). In order to reduce the background noise, the matrix was actively shielded with BGO and CsI(Tl) scintillators. Fig. 3 (right-hand side) shows the detector surrounded by its three levels of side shielding. The detector matrix is cooled by a liquid nitrogen dewar, kept at constant pressure during the flight. The focal spot ideally is on the central detector of the 3x3 Ge matrix, but during flight the spot may wander around on the Ge-detector as the primary stabilization seeks its central position (see Sec. 4.3). The 9 detectors are hereafter identified by their number, from 1 for the upper left detector to 9 for the lower right one. During the flight, all 9 Ge detectors showed nominal performances with practically no line shifts.

4.3. The Pointing System

CLAIRE's stabilization and pointing system has been developed by the balloon division of CNES, with the help of the Observatoire de Genève, Switzerland. The lens is mounted on a fine pointing system with a gimbal mount situated on the upper platform (see Sec. 4 and left-hand side of Fig. 3). The Sun is used as guide star since it is very close to the Crab Nebula around June 14^{th} (about 1 deg). A sunsensor with an offset mechanism, mounted on the inner gimbal frame, guarantees pointing information at a high rate. The absolute pointing requires also the knowledge of the field of view rotation, which was given by an inclinometer mounted on the lens frame. The principle of fine pointing system is summarized in Fig. 4. The solar sensor offsets were checked by two CCD cameras, co-aligned with the lens, and giving the position of the Sun in their field of view. The wide field CCDs and the offsets mechanisms allowed a 7-days launch window.

The primary pointing system stabilizes and points the entire telescope in order to keep the detector aligned with the lens. The primary pointing corrections are made through the help of an azimuthal pivot (which also measures the torque between gondola and balloon) and a zenithal actuator (screw-jack).

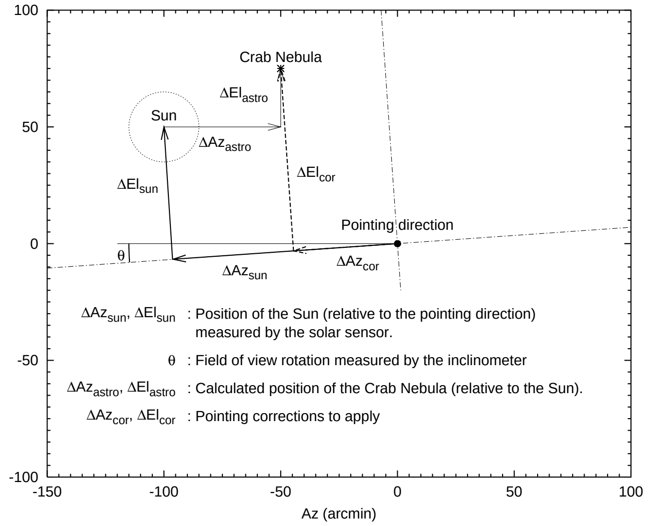

Figure 4. Principle of the fine pointing system. The frame corresponds to the celestial reference, while the dot dashed lines represent the instrument (i.e. CCD camera) axes.

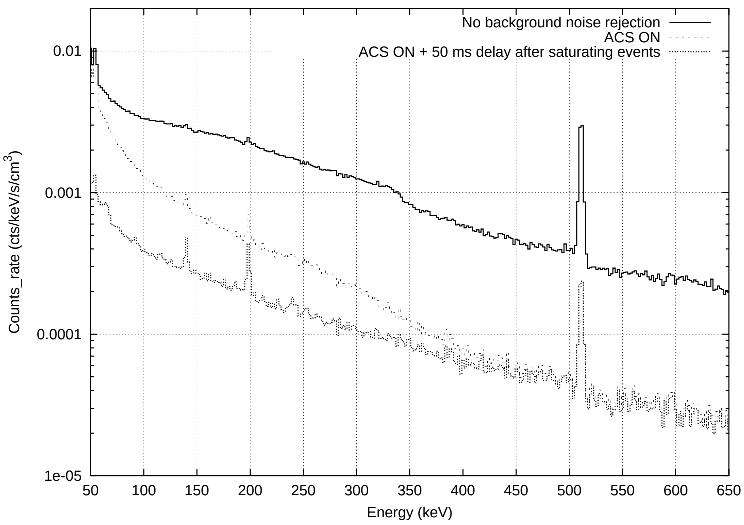

Figure 5. Background spectra recorded at float altitude for single events

5. ANALYSIS OF THE 2001 CLAIRE FLIGHT

5.1. Background Analysis

The reduction of the background noise introduced for the 2001 flight is based on an active anti-coincidence shield (ACS) and on strictly flagging the events detected less than 50 ms after a failure of baseline restoration (usually due to saturating events). Fig. 5 shows the recorded spectrum for single events in the whole matrix during flight at float altitude. The upper curve is the spectrum obtained with no background rejection and the lower one when the flags of the ACS and the saturating events are taken into account. By this method the background noise is reduced by a factor of about 10 at 170 keV. After background rejection and in the range from 50 to 600 keV, four background lines are significantly observable :

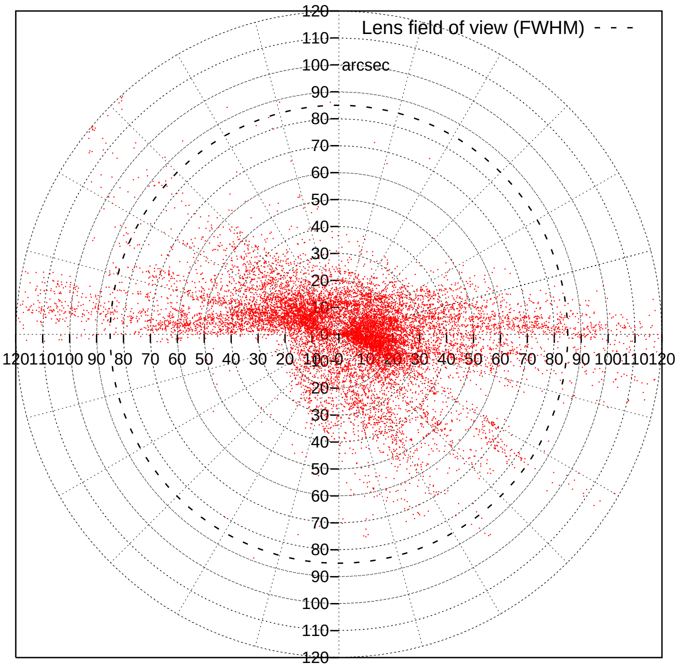

Figure 6. Position of the Crab Nebula as seen by the lens at float altitude. The lens axis is at the center of the graph.

- Ge β decays lines : 53.44, 139.68 and 198.4 keV
- e^+-e^- annihilation line at 511 keV

The low background noise levels achieved during this flight demonstrate the interest of small HP-Ge detectors in γ-ray astrophysics.

5.2. Pointing Accuracy

The fine pointing system described in Sec. 4.3 achieved very good performances. Fig 6 represents the position of the Crab nebula, as seen by the lens, during the flight at float altitude. The lens FOV (about 85 arcseconds FWHM) is drawn with a bold dotted line. Each point represents the mean position of the Crab nebula during 1 s. The Crab pointing accuracy was better than 90 arcseconds during 3h30 with a pointing quality better than 35 arcseconds during 3/4 of this time. The fine pointing system allows sufficiently accurate pointing of the lens axis relative to the sky. However, the position of the focal spot on the detector matrix depends on the primary pointing system (see Sec. 4.3). To keep the focal spot on the matrix, or on the central detector requires a primary pointing accuracy of ± 28 arcminutes, or of ± 9 arcminutes, respectively. Due to the imperfect stability of the azimuthal axis, the focal spot was mainly oscillating from the right (detector 4) to the left (detector 6) sides of the matrix with a period of 170 s. Fig. 7 is a cumulative 2D-histogram of the pointing time on the detector matrix during the time when the fine pointing quality was better than 90 arcseconds. The focal spot appears to have been mainly between detector 5 and 6. Based on the (simulated) spatial distribution of the detectors efficiency and the point spread function of the lens, only single events with a focal spot located in a 1.4 cm diameter circle centered on a detector element have a high enough detecting probability to be useful. Pointing performances are summarized in Table 1.

5.3. The Search for an Astrophysical Signal

As usual in γ -ray astrophysics, the recorded spectra are dominated by background noise, mainly due to secondary emission induced by cosmic rays (e.g. see N. Gehrels, 1992, Ref. 4). In order to optimize the

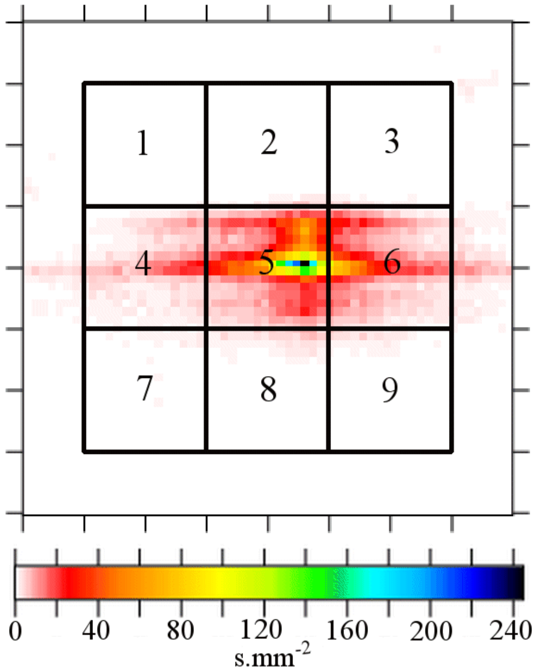

Figure 7. Position of the focal spot on the 3x3 Ge matrix during Crab pointing

Total flight		:	8^h45
Time at float altitude		:	5^h15
Crab pointing	$< 90''$	:	3^h40
	$< 30''$	:	2^h20
Det pointing	on matrix	:	4^h04
	on det 5	:	2^h13
Crab pointing $< 90''$ AND			
	on matrix	:	2^h45
	on det 5	:	1^h40
	on det 5 or 6:		2^h25

Table 1. Pointing performances

detectability of the signal above background, it is necessary to carefully select good time intervals. As previously mentioned, one has to keep single events in time intervals for which the pointing quality was better than 90 arc seconds and the focal spot within a 1.4 cm diameter circle centered on detector 5 or 6. A preliminary spectrum resulting from this analysis is shown on Fig. 8. The diffracted signal from the Crab Nebula is expected as an additional gaussian peak at 170 keV. Simulations, making use of the achieved pointing and the diffraction efficiencies measured in the laboratory show that about 40 events in detector 5 and 20 in detector 6 should have been detected. This number would lead to a 4.5-σ detection (see simulated spectrum on fig. 9). It is apparent that there is no equivalent peak visible in the flight spectrum. While the analysis of the flight data is still in progress, the following critical points could be (alone or in part) responsible for an absence of the signal :

- A yet unidentified alignment problem such a misalignment of the lens axis or a problem with one or several attitude sensors - e.g. the information given by the inclinometer (measuring field of view rotation) may be spurious. However, this shouldn't be crucial since an error of 1 deg in field rotation results in a Crab

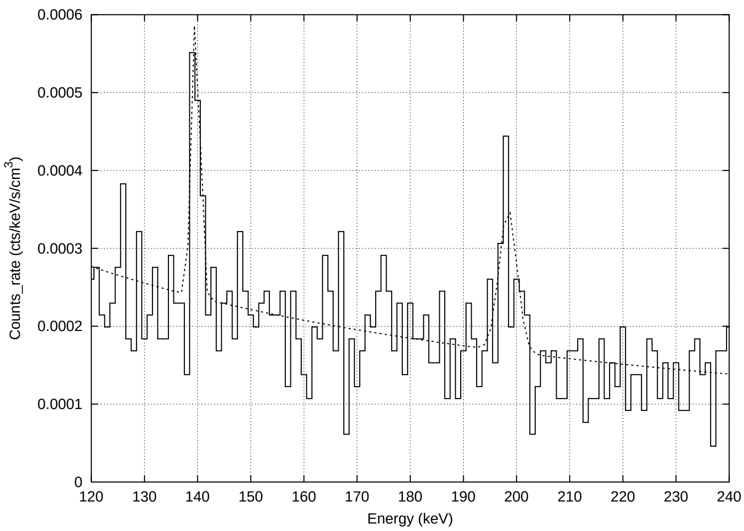

Figure 8. Reduced spectrum for single events in det 5 and 6 during Crab pointing (see text)

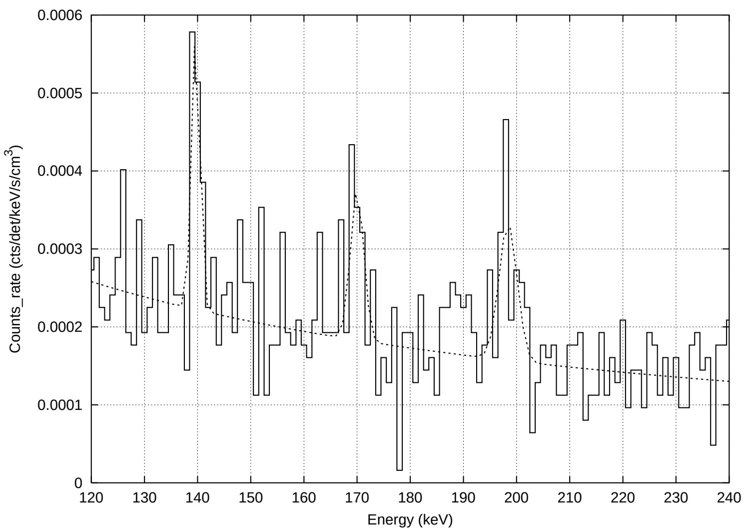

Figure 9. Simulated reduced spectrum for single events in det 5 and 6 during Crab pointing, measured lens and detector efficiencies

pointing error of only about 2 arcmin on June 14.

- The focal spot may have shifted with respect to the detector due to mechanical deformations during the flight.
- For a still unknown reason the efficiency of the lens at 170 keV (for a parallel polychromatic beam) may have been lower than calculated from measures at 122 keV, made with divergent polychromatic and monochromatic beams.

These items are presently under study at CESR. Also, the lens is undergoing further tests on its tuning bench at the CESR in order to validate the diffraction models used for the 2001 flight. We are confident that this work will shed new light on the results of the CLAIRE 2001 flight.

6. CONCLUSION

Despite the fact that so far no significant signal has been detected, the CLAIRE 2001 flight demonstrated that testing the γ-ray lens on a stratospheric balloon is feasible.The pointing systems achieved very good accuracy, whereas the actively shielded detectors showed low background noise for a stratospheric flight. The CLAIRE payload is presently being upgraded and is scheduled for a transmediterranean balloon flight in June 2003. After having demonstrated the gamma-ray lens as a tool for nuclear astrophysics, further balloon flights could use a lens tuned for higher energy - e.g for the study of the 511 keV annihilation line.

Ultimately, the crystal diffraction lens will be put in space where longer exposures, longer focal length and steady pointing will result in outstanding sensitivities. A space borne crystal telescope will use a gamma ray lens situated on a 3-axes stabilized spacecraft, focusing gamma rays on a small HP-Ge detector. The detector system will be situated on another small spacecraft, stabilized to a precision of about 1 cm^3, 130 meters from the lens spacecraft. Made of two large Cu and Ge rings (respectively 176 cm and 222 cm diameters) such a crystal lens will observe in two 100 keV wide energy ranges around 500 keV and 850 keV, with a sensitivity of a few 10^{-7}photons$\cdot s^{-1} \cdot cm^{-2}$.

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