Development of efficient Laue lenses: experimental results and projects

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ABSTRACT

Laue lenses are an emerging technology allowing the concentration of soft gamma rays in the ∼ 100 keV - 1.5 MeV energy range. Two lens designs based on recently measured crystals are presented in this paper. A lens dedicated to the understanding of the progenitors and explosion physics of Type Ia supernovae through the observation of the 847 keV line produced by the decay chain of the radionuclide ^{56}Co. With a Compton camera at the focus (as proposed for the DUAL mission), we find that a space-borne telescope could reach a 3-σ sensitivity of 1.5×10^{-6} ph/s/cm^2 for a 3% broadened line in 10^5 s, enabling the detection of several events per year with enough significance to strongly constrain the models. On the other hand, a second generation prototype is proposed. Made to realize a balloon-borne telescope focusing around the electron-positron annihilation line (511 keV), this lens would primarily be a technological demonstrator. However with an estimated sensitivity of 5×10^{-6} ph/s/cm^2 in 10^4 s observation time, this Laue lens telescope could bring new hints in the search of the origin of the Galactic positrons. To build this prototype, a dedicated X-ray beamline has been built at the Space Sciences Laboratory.

Keywords: Soft gamma rays; Telescope; Focusing gamma rays; Bragg diffraction; Crystals;

1. INTRODUCTION

Laue lenses are an emerging technology allowing the concentration of soft gamma rays in the ∼ 100 keV - 1.5 MeV energy range. The concentration of the signal collected from a large area onto a small detector is a way to beat the instrumental backgrounds that hamper the observation in this energy domain. The background being roughly proportional to the volume of the detector, focusing appears as the only solution to get the sensitivity leap with respect to currently operating instruments required to address some key science topics.

One such topic is the understanding of the Type Ia supernovae (SNe Ia) explosion mechanism. Despite the fact that they are used as standard candles to constrain the expansion rate of the Universe over its history, the SN Ia explosion mechanism is not fully understood yet. The commonly accepted scenario for these events involves a C/O white dwarf (WD) in a close binary system that accretes matter from its companion star up to the Chandrasekhar mass limit, 1.38 $M_\odot$. At this point, the temperature and pressure conditions near the center allow the carbon to ignite, leading to a thermonuclear flame propagating outward.[1] However there are many alternative scenarios that can lead to SNe Ia involving in particular the sub-Chandrasekhar explosion of C/O WD triggered by the detonation of a superficial He layer accreted from the companion star, or the coalescence of two WD.[2] The common point of all the SNe Ia models is the large quantity of ^{56}Ni synthesized (∼ 0.1 to 0.9 $M_\odot$). The decay chain ^{56}Ni (6.1d) $\rightarrow$ ^{56}Co (77d) $\rightarrow$ ^{56}Fe produces many gamma-ray lines and is believed to power the entire visible emission of the supernova. The observation of these lines reveal the location of the radioactivity within the ejecta through the time-dependence of the photon escape, and the ejection velocities of various layers through the line Doppler profiles. Therefore, spectroscopy and light curve measurements of these gamma-ray lines allow direct measurement of the underlying explosion physics and dynamics, and thus

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discriminate among the competing models. Two lines at 812 keV and at 847 keV are of particular interest for this purpose. SNe Ia are ideal targets for a focusing telescope as they are point sources of known position. As shown in this paper a Laue lens telescope (LLT) is a very promising option to finally understand what are the progenitors of these events and the physics of the explosion.

Another key topic of sub-MeV astrophysics is the origin of the Galactic positrons, which emit an annihilation line at 511 keV that is currently observed by INTEGRAL/SPI (see e.g. Refs 3, 4). The presently observed emission has a peculiar spatial distribution composed of a bright bulge centered on the Galactic center and a faint disc. No point sources are seen by SPI so far. An asymmetry in the inner disc emission was recently reported,[5] which somewhat resembles that observed in the distribution of the low mass X-ray binaries (LMXB). SPI having an angular resolution of $\sim 3°$, the emission observed towards the Galactic center is compatible with the sum of unresolved point sources. However, many authors point out that compact objects in binary systems featuring an accretion disc are likely to create positrons with a kinetic energy of ~ 1 MeV, which they must lose before annihilating if a narrow line - as that observed - is to be produced. The propagation range is largely unconstrained as it depends of a large number of parameters such as the interstellar medium density, temperature and ionization state and the structure and turbulence of the Galactic magnetic field. Depending on the assumptions of different authors it can range from a couple of parsecs up to Galactic distances.

After more than 30 years of observation of this annihilation line from the Galactic center, despite huge progresses in the characterization of the emission, neither the sources of the positrons or their diffusion range before annihilation is known. To bring new hints, more sensitive observations are required on both large and small angular scale. Importantly these observations must be done with high spectroscopic resolution. As proposed in this paper, a balloon-borne LLT could allow us to probe with high sensitivity some candidate sources, such as nearby black hole candidate in binary system and young pulsars. The mapping of the inner part of the Galactic center would also reveal if the diffuse emission seen by INTEGRAL/SPI is homogeneously diffuse or contains some overly dense structures.

In this paper, we first present the state of the art of Laue lens development. After describing the principle of these lenses, we present the concept of a second generation prototype for a balloon focusing around the electron-positron annihilation line at 511 keV. Then, we present a design and performance of a satellite-borne LLT devoted to the observation of the 847 keV emitted by SNe Ia. In section 6, we show that the crystals required for these two lenses exist, and were recently measured. We finally report on the status of the dedicated X-ray beamline currently being assembled at the Space Sciences Laboratory (SSL), which will serve to assemble our prototype.

2. LAUE LENS PRINCIPLE

A Laue lens concentrates gamma-rays using Bragg diffraction in the volume of a large number of crystals arranged in concentric rings and accurately oriented in order to diffract radiation coming from infinity towards a common focal point (see e.g. Ref. 6). In the simplest design, each ring is composed of identical crystals, their axis of symmetry defining the line of sight of the lens (c.f. Figure 1).

Bragg's law links the angle θ_B between the rays' direction of incidence and the diffraction planes to the diffracted energy E through the diffracting planes d-spacing d_{hkl}:

$$2d_{hkl}\sin\theta_B = \frac{hc}{E} \;\;\Leftrightarrow\;\; 2d_{HKL}\sin\theta_B = n\,\frac{hc}{E} \tag{1}$$

with h, k, l the Miller index defining the set of diffracting planes at work (another notation uses H, K, L prime numbers and n the order of diffraction), h the Planck constant and c the velocity of light in vacuum. Considering a focal distance f, the mean energy diffracted by a ring only depends on its radius r and the d-spacing of its constituent crystals[7] :

$$E = \frac{hc}{2d_{hkl}\sin\left(\frac{1}{2}\arctan\left(\frac{r}{f}\right)\right)} \propto \frac{f}{d_{hkl}\,r} \tag{2}$$

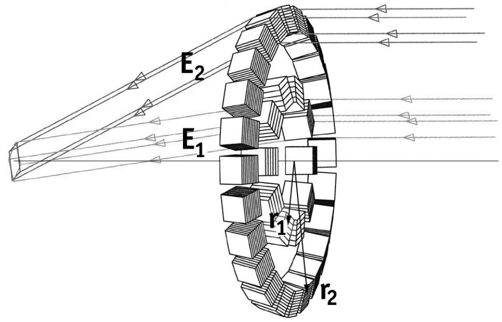

Figure 1. Laue lens principle. Depending on the material and reflection of the crystals, E_1 and E_2 can be equal or not (see text for details). Typically, crystal size ranges between 0.5 cm and 1.5 cm.

As we understand from equation (2), if the variation of radius is compensated by a change in the d-spacing of the crystals, a unique energy can be diffracted by several rings ($E_1 = E_2$ in Fig. 1), which allows a higher effective area on given energy bands. However, if the same crystals and reflection (i.e. the same d-spacing) is employed on many adjacent rings, a continuous energy band is obtained (and $E_1 > E_2$ in Fig. 1).

Practically, the principle is applicable from ∼100 keV up to ∼1.5 MeV, limited at the low end by the fact that the crystals' thickness maximizing the reflectivity becomes too small to allow their safe handling, and by the reflectivity that becomes too low at the other end. Although Laue lenses are better adapted to cover relatively narrow energy bandpasses, it is possible to get a sizable effective area over a continuous energy band as large as about half an order of magnitude wide as demonstrated for instance in Ref. 8 and 9.

3. LAUE LENS DEVELOPMENT STATUS AND MOTIVATION FOR A SECOND GENERATION PROTOTYPE

Laue lenses have been studied for several years, with many noticeable achievements. Mainly financed by the French, Italian and European Space Agencies (CNES, ASI and ESA), independent activities led to major improvements in many key technological areas as summarized in the following:

Prototypes: In the 90's and early 2000's, the CLAIRE prototype lens (built at CESR, France) demonstrated the successful operation of a Laue lens (CNES funded).[10] Composed of 556 mosaic $Ge_{1-x}Si_x$ crystals tuned to focus at 2.79 m a narrow energy band centered on 170 keV, this lens has been extensively tested during ground tests and two balloon flights. It detected the Crab nebula during the second flight. This team is now working in collaboration with Thales Alenia Space to build a small prototype module aiming to achieve a 10-arcsec crystal orientation accuracy and a dense packing factor (CNES funded). This activity is still on-going.

At the University of Ferrara (Italy), a first prototype made of 20 Cu mosaic crystals (mosaicity of ∼ 3 arcmin) was assembled in 2007 on a carbon fiber substrate[11] (ASI funded). The orientation accuracy reached was of the order of a few arcmin. The method used would allow for a dense packing factor. The Ferrara team is currently assembling a second prototype made of Cu crystals on a refined carbon fiber substrate limiting the thermal distortions with the goal of reaching an orientation accuracy of the order of 1 arcmin.[12]

Mission design: In 2004, the MAX[13] mission was proposed to CNES and studied for one year in pre-phase A. It gave us an estimate of the mass that represents a lens substrate, and showed that the modular structure is a good way to build it. Importantly, it showed that a passive thermal control can limit the temperature variation of the lens to 1°C, which is sufficient to ensure a nominal performance.

The Gamma-Ray Lens ESA technological reference study (ESA Funded) investigated the possibility of building a very large Laue lens telescope. One of the main outcomes was the identification of the technological areas where improvements are mandatory to allow the realization of a large scale space-borne Laue lens telescope.[14]

In 2007, the Gamma-Ray Imager (GRI) mission proposal[15] for the Cosmic Vision AO1 gave another example of lens configuration. The writing of the proposal triggered many studies in collaboration with industrial partners such a new engineer lens design, an estimate of its mass, and a parallelized way to assemble it based on its modular structure.

Crystals: The growth and cut of $Ge_{1-x}Si_x$ mosaic crystals was developed for the CLAIRE project. It is now very well mastered.[16]

Mosaic copper and $Si_{1-x}Ge_x$ with gradient of concentration (which creates curved diffracting planes) were studied within the Gamma Ray Optics Development activity (ESA funded). This study especially addressed the reproducibility of the growth and cut of crystals in an industrial fashion. It proved that Cu and SiGe crystals that were composing the GRI lens are available with the right bandpass, and allowed a statistical study of the rejection rate during their production (results to be published soon).

Recent work opened the way towards high-Z crystals giving much more efficiency at energies above 500 keV than Cu and Ge (see e.g. Ref. 17, 18). Thanks to a collaboration with Mateck GmbH, many pure heavy metal crystals have been identified as usable for a Laue lens, as shown in section 6.

Software: The combined contributions of Hubert Halloin, Nicolas Barriere, Julien Rousselle and Jurgen Knödlseder enabled a complete set of Laue lens simulations to be obtained. Many tools have been created to design Laue lenses and predict their performance: Effective area, PSF, imaging capabilities. The tests of the CLAIRE prototype allowed the validation of these simulation tools.

Valuable knowledge is being accumulated in a number of fields. However, none of the above projects is aimed to gather all the specifications required for a space-borne mission in a prototype. This is why we propose to build a second generation prototype at SSL, fully representative of what would be the lens of a LLT focusing a bandpass centered on 847 keV.

The main features are the dense packing factor (0.5 mm between crystals), the orientation accuracy (goal: 10 arcsec, requirement: 20 arcsec), the resistance to thermocycles and to vibrations, and importantly the use of crystals suitable for a high energy lens. After calibration and environmental tests, this prototype will be used for the realization of a balloon-borne telescope. Unfortunately SNe Ia are not ideal targets for a balloon-borne LLT. They are transient objects, and the minimum focal length yielding a high enough sensitivity is $\sim$ 30 m. However the best crystals for a SNe Ia lens are also perfectly suited for the diffraction at 511 keV. As shown in section 4, a very appealing effective area can be achieved with a 8-m focal length, which can be flown onboard a balloon gondola.

4. A BALLOON BORNE LAUE LENS TELESCOPE TO OBSERVE AT 511 KEV

The current design for a 511 keV balloon-borne LLT has a focal length of 8 m. The lens is composed of 5000 crystals (sorted by decreasing number: rhodium, lead, silver and germanium) measuring 5x5 mm^2 each and having a mosaicity of 75 arcsec. The thickness of each crystal is calculated to maximize the reflectivity. The crystals are distributed over 32 concentric rings, covering radii from 4.5 cm up to 23 cm as shown in Fig. 2. The total mass of crystals amounts to 10 kg, which means that the entire lens, including the substrate, would not exceed $\sim$25 kg.

Considering a Gaussian distribution of σ= 20 arcsec for the crystal orientation around their nominal angle (65% of crystals oriented to better than 20 arcsec) and a mean crystallite size for the model of mosaic crystals of 80 μm, the effective area exceeds 40 cm^2 between 490 and 525 keV, peaking at 511 keV to 47 cm^2 (Fig. 2).

The point spread function (PSF) for an on-axis source encircles 65% of the diffracted photons in a radius of 3.4 mm, the half-power radius (HPR) being 2.8 mm (Fig. 3). Knowing that the goal for the crystal alignment is a distribution of $\sigma = 10$ arcsec, these values can be seen as conservative.

To compute the sensitivity, we considered for the focal plane instrument a stack of 5 Ge cross strip planar detectors identical to that composing the Nuclear Compton Telescope[19] (NCT). These detectors measure 8×8×1.5 cm^3, with a strip pitch of 2 mm which gives a 3-D localization of the events within 2×2×0.5 mm^3. For a balloon

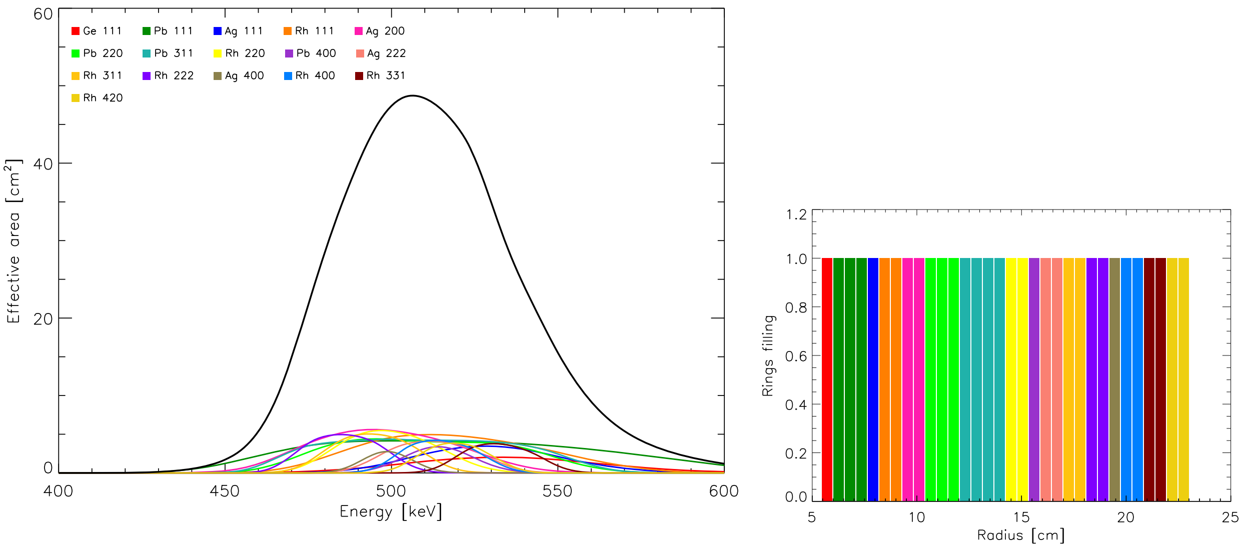

Figure 2. Effective area of the 511 keV lens for a point source on axis. The black curve shows the total effective area while the color curves show the contribution of each crystal material and reflection. The mosaic crystals are modeled with a mean crystallite size of 80 μm, and the crystals are oriented according a Gaussian distribution of σ=20 arcsec around their nominal angle, which makes this effective area estimate conservative.

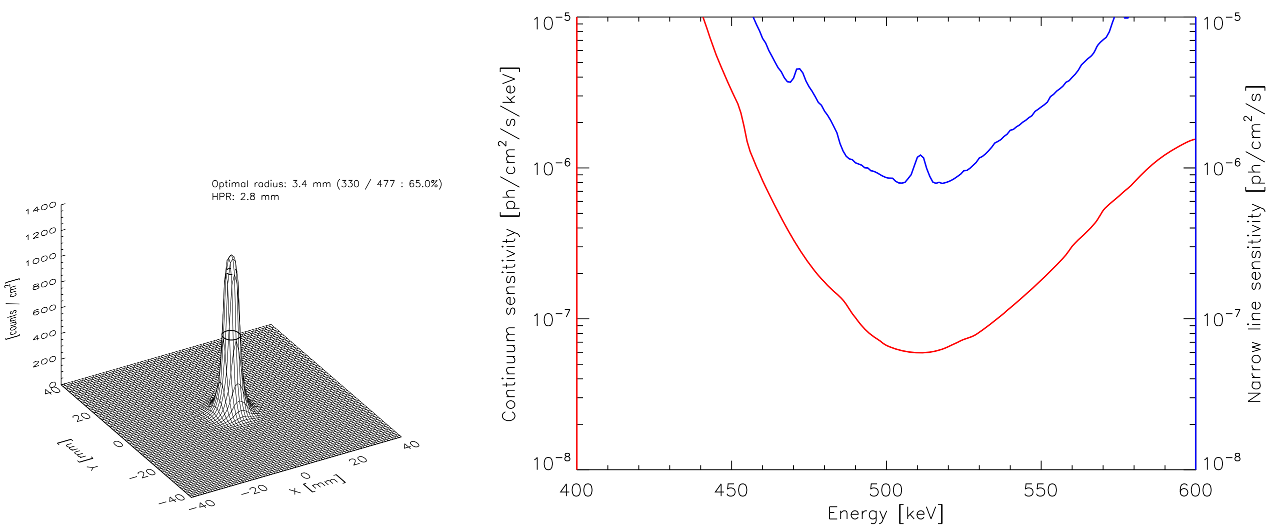

Figure 3. *Left:* focal spot of the 511 keV lens for an on-axis point source emitting a 2-keV wide narrow line centered on 511 keV, and (*right*) 3-σ sensitivity of the telescope for 100 ks observation time. The red curve represents the continuum sensitivity (for $\Delta E/E = E/2$) while the blue one shows the narrow line sensitivity.

flight, an active BGO collimator would have to restrict the field of view to the lens. Considering this option, a 3-σ sensitivity of 1.5×10^{-6} ph/cm^2/s in 10^5 s (i.e. 5×10^{-6} ph/cm^2/s in 10^4 s for a balloon flight) can be achieved, as shown in Fig. 3.

This outstanding sensitivity relies on two facts: firstly, the lens concentrates 0.65×47 cm^2 onto 0.36 cm^2, with represents a gain of 84. Secondly, the use of 3-D positioning detectors gives many advantages:

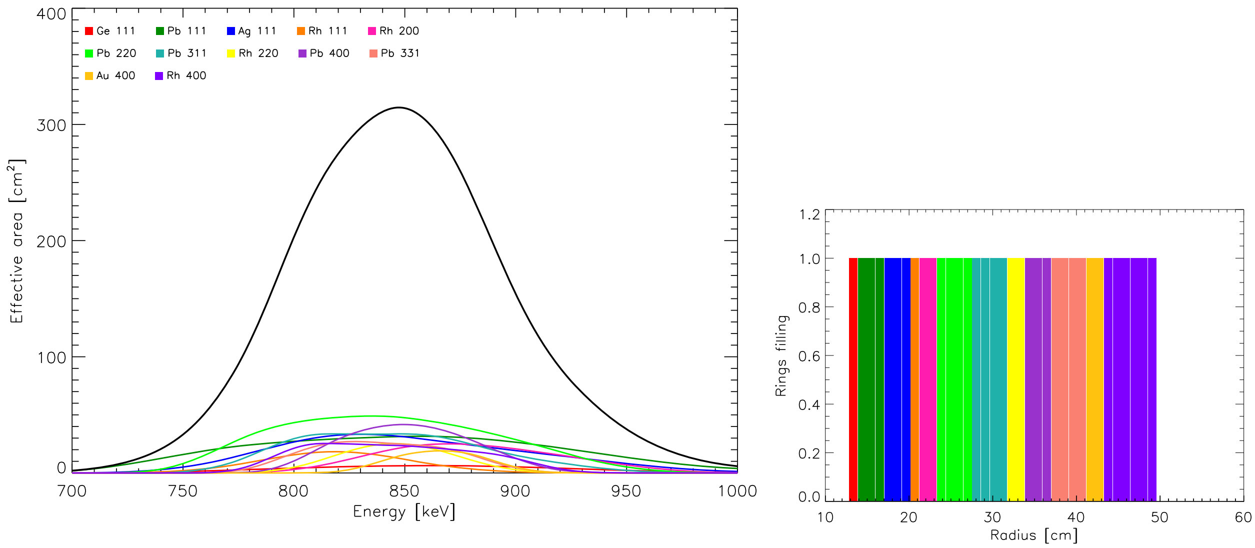

Figure 4. On-axis point source effective area of the proposed lens for the DUAL mission. The black curve shows the total effective area while the color curves show the contribution of each crystal material and reflection. The mosaic crystals are modeled with a mean crystallite size of 80 μm, and the crystals are oriented according a Gaussian distribution of σ=20 arcsec around their nominal angle.

- It allows the reconstruction of the lens PSF. This gives the possibility of building an image of the sky, but also the position of the signal in the focal plane, which consequently enables the simultaneous measurement of the background in the remaining part of the focal plane.
- The Compton reconstruction allows for the rejection of the events for which the circle of possible incidence direction does not intercept the lens. This is a powerful way to further reject the instrumental background.

Due to the fact that the Laue lens is actually a concentrator, the PSF becomes an annulus with a modulation of intensity when the point sources moves off-axis. This does not prevent a deconvolution of the image of the sky, but the signal is spread over the focal plane, which leaves less surface for the instrumental background evaluation and dilutes the signal in more background. This effect is accompanied by a diminution of the effective area. In fact the integrated effective area remains roughly constant, but the curve spreads and flattens, which could be positive for the observation of a continuum but not for a line. These combined effects imply the degradation of the sensitivity by a factor of 10 when the point source moves off-axis by 10 arcmin. Despite this fact, a 8×8 cm^2 focal plane would allow a field of view (FoV) of ± 15 arcmin. The sensitivity for an extended source still needs to be properly evaluated, and will be addressed, along with detailed imaging capabilities, in an upcoming paper.

5. DUAL: A SATELLITE MISSION TO FOCUS ON TYPE IA SUPERNOVAE

DUAL is a concept of satellite mission that was recently proposed as a white paper for US National Academy of Sciences Decadal Survey Astro2010[20] . The aim is to perform simultaneously an all-sky survey in the 0.1-10 MeV energy range and pointed observations to SNe Ia with a Laue lens focusing in the 800 - 900 keV range. The key point is that a single medium-sized compact Compton telescope is the focal instrument for the lens and the all-sky monitor. In this section, we present a Laue lens design that could suit this mission concept.

The focal length for this lens is set to 30 m. According to several manufacturers (for instance ATK or Northrop Grumman), this distance can be realized by an extendible mast, for instance as an upscaled version of that designed for the NuSTAR mission. The lens is composed of ~5000 crystals of 1x1 cm^2 made out of (by order of decreasing number): lead, rhodium, gold, silver, and germanium. The crystals are distributed over 35

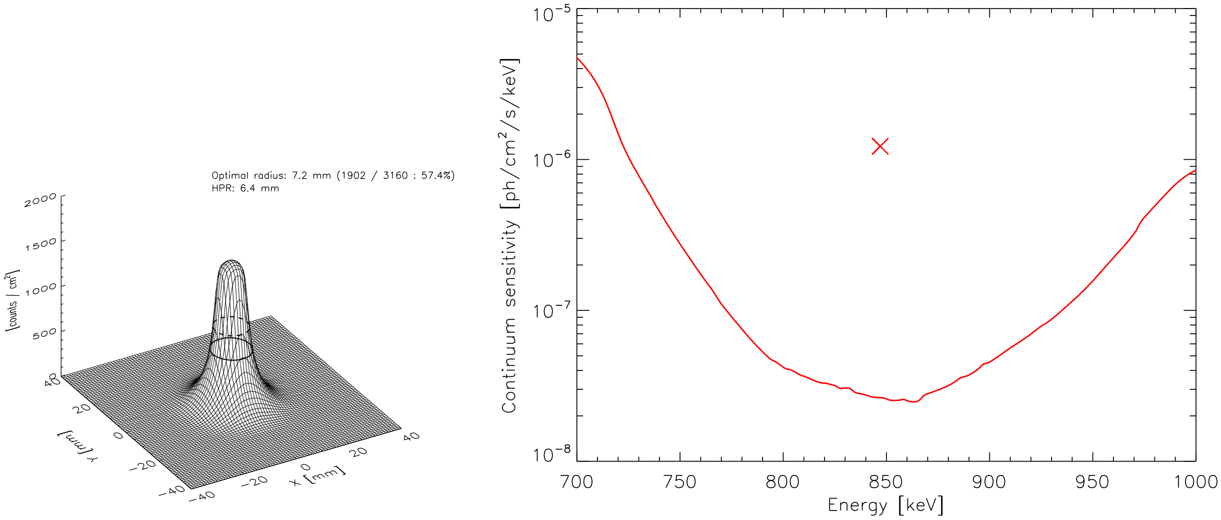

Figure 5. 847 keV LLT performance. *Left:* PSF for an on-axis point source. *Right:* 3-σ sensitivity for an observation time of 10^5 of a continuum ($\Delta E/E = E/2$). The cross indicates the sensitivity for a 3%-broadened line at 847 keV.

rings, which radii span from 12.5 cm to 49.5 cm (Fig. 4). The total crystal mass amounts to 58 kg, which, according to previous mission studies,[13,15] corresponds to a full lens mass (including the structure) of ∼120 kg.

As in the case of the 511 keV, a Gaussian distribution of 20 arcsec of standard deviation has been considered for the crystal orientation. The effective area reaches 315 cm^2 at 847 keV and is above 280 cm^2 in the 825 keV - 870 keV range. The PSF for an on-axis point source (the relevant case for SNe Ia observation) encircles 57% of the signal in a radius of 7.2 mm (1.6 cm^2), the HPR being 6.4 mm (Fig. 5).

The sensitivity presented in Figure 5 was computed considering the same kind of Compact Compton detector made of many stacked cross-striped Ge planars. With this option, the 3-σ sensitivity for an observation time of 10^5 s is $\sim 1.5\times10^{-6}$ ph/cm^2/s for a 3% broadened line at 847 keV (indicated by the cross in Fig. 5), while the continuum sensitivity (for $\Delta E/E = E/2$) reaches 2.5×10^{-8} ph/cm^2/s/keV.

Such an unprecedented sensitivity would enable study of SNe Ia out to 50-80 Mpc, for dozens of potential targets each year.[20] Enough to discriminate between the currently competing models, and determine their progenitor and explosion physics.

6. CRYSTALS FOR THE 511 KEV AND 847 KEV LENSES

Over the two past years several crystal samples provided by Mateck GmbH were measured at ESRF (beamline ID15A). The main aim of these experiments was to evaluate the quality of commercially available high-Z pure mosaic crystals. Mosaic crystals are imperfect single crystals which are modeled as an assembly of tiny perfect crystals, the crystallites, which are slightly misaligned with respect to each other according to a Gaussian distribution (more details in e.g. Ref. 7 and 17). The main quality criterion is the mosaicity (also called sometimes mosaic spread) which refers to the full width at half maximum (FWHM) of the angular distribution of the crystallites. As seen in the two previous sections, the mosaicity for high energy Laue lenses should be in the 0.5 - 2 arcmin range.

Figure 6 shows rocking curves (RC) measured on four crystal materials of interest for the two lenses presented before: rhodium, lead, silver and gold. A RC probes the angular distribution of the crystallites as it is a measurement of the diffracted and transmitted monochromatic beam as a function of the incidence angle onto the crystalline planes. The RCs presented in Fig. 6 have been centered on the Bragg angle of each crystal, and are normalized such that the diffraction efficiency is directly read. We don't show the reflectivity here

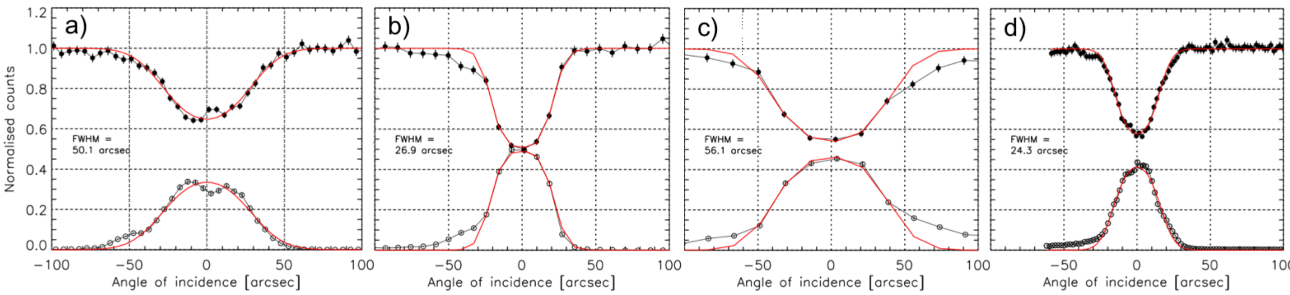

Figure 6. Rocking curves recorded at ESRF in March 2009 and May 2010, using the beamline ID15A. The two complementary curves plot the transmitted intensity (filled circles) and the diffracted intensity (open circles) as a function of the incidence angle of the beam. The red curve is a fit to the data of Darwin's model using the dynamical theory of diffraction. From the left to right: a) 10-mm thick Rh 220 crystal measured at 500 keV; b) 12-mm thick Pb crystal measured at 700 keV; c) 10-mm thick Ag 111 crystal measured at 500 keV; d) 2-mm thick Au 111 crystal measured at 588 keV.

(ratio of the diffracted to incident beam intensities) because the crystal thicknesses are not optimized, making it irrelevant. Table 1 summarizes the results. The important point to notice is that the crystals we are using in the lens simulations presented in this paper can actually be produced with the proper mosaicity.

Table 1 also gives the crystallite size that is extracted from Darwin's model fit to the data. This parameter is of prime importance for the mosaic crystal model as it tunes the diffraction efficiency for a given mosaicity. Roughly speaking, the smaller it is the better is the diffraction efficiency. But the reality is that Darwin's model is not perfectly adapted to pure metal mosaic crystals. We actually observe that the crystallite size increases with increasing energy. This parameter also varies significantly from one reflection to another in the same crystal. By using a value of 80 μm in our lens simulations, we believe this to be conservative. Dedicated future experiment will investigate the energy and reflection dependence of this parameter for the selected materials.

Crystal	Reflection *hkl*	Thickness (mm)	Energy (keV)	Mosaicity (arcsec)	Crystallite size (μm)	Quality factor
Rh	220	10	500	50	90 ± 3	0.80
Pb	111	12	700	27	114 ± 3	1.0
Ag	111	10	500	56	67 ± 5	0.92
Au	111	2	588	24	65 ± 2	0.87

Table 1. Summary and analysis of the measurements presented in Fig. 6. The quality factor is defined as the ratio of the measured diffraction efficiency to that calculated using the most optimistic model of mosaic crystal (the kinematic theory which assumes negligible crystallite size).

7. SSL HARD X-RAY FACILITY

An X-ray beamline fully dedicated to the development and realization of a second generation Laue lens prototype was recently setup at SSL. As visible in Figure 7, the construction is completed, we are currently in the commissioning phase. The radiation source is a liquid cooled X-ray generator (lent by CESR, France) producing a continuum spectrum up to 150 keV with a current of 500 μA. At the other end, we use a NCT prototype (high purity Ge cross-strip planar detector) as detector.

In the first phase of our activity, this beamline will be used to develop an orientation and fixation method in order to establish an assembly process for the prototype. It will also serve the development of curved crystals, not addressed in this paper but very promising to get higher reflectivity. The second phase of this activity is included in an APRA proposal that has been submitted to NASA. If accepted, we will start the assembly of a pie-shaped prototype (a small segment of what would be the 511 keV lens) in order to test, in real conditions, the assembly process and check that this prototype can resist the environmental tests. The third phase is the

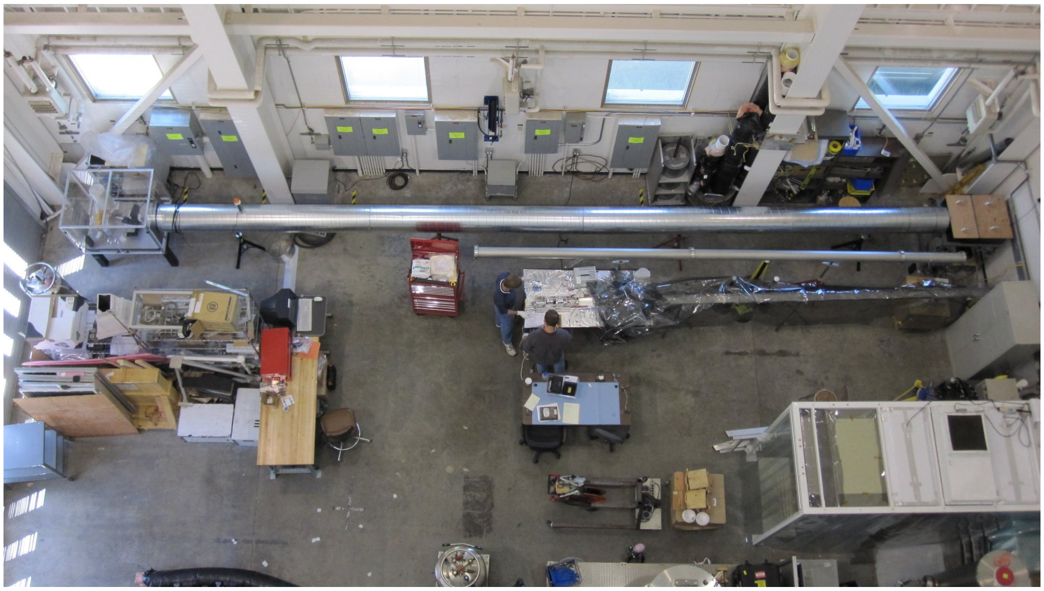

Figure 7. Picture of the 'high bay' at SSL seen from the 4th floor. The Laue lens beamline is the steel pipe along the wall, with at the right end the X-ray generator (covered by lead sheets fixed on wooden panels) and at the other end the experiment table enclosed in a plexiglass box.

actual construction of the 511 keV Laue lens along with a dedicated focal plane in order to perform in-depth ground calibration and eventually a balloon flight.

8. SUMMARY

Laue lens development is reaching a point where all the elements are available to build an efficient lens. To demonstrate it, we propose to build at SSL a second generation prototype that will gather all the requirements for a space-borne LLT. Our main aim with a Laue lens is to to address SNe Ia science, as proposed for the DUAL mission. The recent lens design showed that a very sensitive telescope can be made with a 30-m long extendible mast, sensitive enough to detect SNe Ia out to $\sim$ 50 - 80 Mpc, which would allow the progenitors and explosion physics to be determined in several cases per year. This design is based on crystals for which the measured mosaicity has been found to be in the proper range: lead, rhodium, gold, silver and germanium. We know that the necessary crystals exist, and we now need to develop a method to orient them accurately. This is the purpose of the X-ray beamline that has been setup at SSL. With this tool, we will establish an assembly process and test it with the realization of a pie-shaped prototype. This first prototype will also be the occasion to start a partnership with Mateck GmbH, which produces the crystals. If this first phase is successful, we will be in a position to start the realization of the second generation prototype, which will be a Laue lens focusing at 511 keV compatible with a balloon-borne flight. With an unprecedented sensitivity in the e^+-e^- annihilation line, this technological telescope will bring new hints for the understanding of the origin of the Galactic positrons and their propagation in the interstellar medium.

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