EXPERIMENTAL PROPOSAL FOR A GAMMA-RAY BEAM LINE AT THE SPANISH SYNCHROTRON ALBA: CALIBRATION OF GAMMA-RAY INSTRUMENTS FOR NUCLEAR ASTROPHYSICS

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ABSTRACT

An experimental proposal for the future gamma-ray beam line at the spanish synchrotron ALBA, to be built near Barcelona, is presented. The aim of the proposal is to demonstrate that this line would be very well suited to measure the performance of instruments for gamma-ray astronomy, in the energy range around 1 MeV. The expected intensity of the beam, its high collimation and polarization would provide an unique opportunity to test instruments in the gamma-ray domain, such as the prototype of an innovative LAUE gamma-ray lens for nuclear astrophysics, CLAIRE, and its future development for a space mission, MAX. Important applications in the field of crytallography would give an added value to the proposal, since the characterization of mosaic crystals would be an essential step to the suggested measurements.

1. INTRODUCTION

Nuclear astophysics relies on gamma-ray line astronomy, mainly in the MeV range, to test its predictions. Some examples of gamma-ray lines already detected are the 511 keV line, tracing electron-positron annihilation in the interstellar medium and in the proximity of very compact objects such as black holes or neutron stars, the 1.809 MeV line, showing the galactic sites of the radioactive decay of the ^{26}Al isotope, or the 1.157 MeV line, coming from ^{44}Ti decay in young supernova remnants. However, some other gamma-ray lines still remain elusive, as for instance those emitted during supernova and nova explosions (i.e., ^{56}Co lines at 847 keV and 1.238 MeV, ^{7}Be line at 478 keV or ^{22}Na line at 1.275 MeV). Their detection is the only way to trace the nucleosynthesis of radioactive isotopes during these explosions, and thus to understand their explosion mechanism. Since supernovae are the major sources of the elements in the Universe, the knowledge of their nucleosynthetic activity is a really relevant topic for astrophysics. Other scientific objectives for MeV gamma-ray astronomy include the sun, galactic compact objects, active galactic nuclei, gamma-ray bursts, cosmic gamma-ray background.

The reason for the very rare detections of cosmic gamma-ray lines is that the MeV range faces important challenges from the instrumental point of view. In addition to the general difficulties of gamma-ray detection (few signal photons have to be extracted from very intense backgrounds), the MeV range is specially difficult, since it correponds to the energy range where Compton scattering (with small cross sections) is dominant, making it harder to handle than photoelectric absorption or pair formation, at lower and larger energies, respectively. Actually, the present generation of gamma-ray instruments makes use of geometrical optics - shadowcasting in modulating aperture systems - or quantum optics - Compton scattering. This kind of instruments is faced with the problem that *bigger does not necessarily mean better*. The reason for this apparent contradiction is that the collection area in traditional gamma-ray telescopes should be roughly equal to the detection area. Therefore, the larger the collection area, the larger the detection volume and thus the higher the instrumental background. This means that significative improvements in sensitivity need huge instruments, too expensive for space missions. An innovative concept for detecting gamma-rays in the MeV range, which overcomes this problem and allows for unprecedented sensitivities consists of focusing the gamma-rays from a large collection area onto a small detector.

Last but not least: there is an increasing interest in the high-energy astrophysics community in the use of polarimetry in the MeV range as an important diagnostic tool for the nature of the cosmic sources of gamma-rays. In a recent workshop held in Stanford (USA), a large number of studies related to this topic were presented (see X-Ray Polarimetry Workshop (2004)), showing the potential relevance of polarization measurements and some ways to make it technically feasible. In fact, recent measurements with the RHESSI satellite have shown that this is the case (see Coburn & Boggs (2003) for the detection of polarization in a gamma-ray burst).

A gamma-ray beam line at the future spanish synchrotron ALBA, based on the inverse Compton scattering of laser photons with highly-relativistic electrons from the synchrotron ring, would be extremely useful for the analysis of the performance of a gamma-ray lens and other planned instruments in the MeV domain. There is not at present any other european facility offering this unique opportunity for getting an intense, highly collimated and polarized beam in the MeV energy range.

2. STEPS TOWARDS A GAMMA-RAY LENS FOR NUCLEAR ASTROPHYSICS

Gamma-rays can interact coherently inside a crystal lattice provided that angles of incidence are very small. As a consequence of the small scatter-angles Bragg diffraction in the Laue geometry is more convenient: photons propagate through the entire crystal, using all the crystal thickness for diffraction.

In a crystal diffraction lens, crystals are arranged in concentric rings such that they will diffract the incident radiation of a particular energy onto a common focal spot where the detector is placed (Fig. 1).

In order to be diffracted, an incoming gamma-ray must satisfy the Bragg-relation:

$$2\ d_{[hkl]}\ sin\theta\ =\ n\ \frac{hc}{E} \tag{1}$$

where d is the crystal plane spacing, θ the incident angle of the photon, n the reflection order, and E the γ-ray energy. A crystal at a distance r from the optical axis is oriented so that the angle between the incident beam and the crystalline plane is the Bragg angle θ.

Laue diffraction lenses have demonstrated their potential in laboratory measurements (Smither 1989, von Ballmoos and Smither 1994, Naya et al.1996, Köhnle et al.1997)

The CLAIRE project, developed at CESR, was born to prove the principle of a Laue diffraction lens for nuclear astrophysics. Its natural continuation is a project for a space mission named MAX (for Max von Laue).

2.1. CLAIRE

CLAIRE is a balloon-borne telescope dedicated to validating the concept of a crystal diffraction lens for nuclear astrophysics (see Laporte et al. (2000)). CLAIRE's lens consists of 556 Ge-Si mosaic crystals, focusing 170 keV γ-ray photons onto a 3x3 matrix of

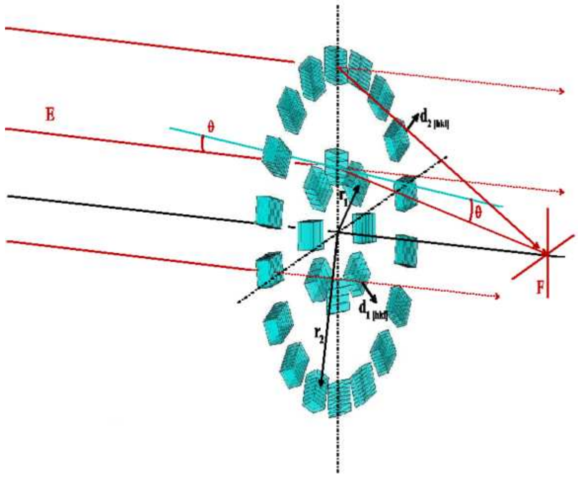

Figure 1. The basic design of a crystal diffraction lens in Laue geometry. Crystals are disposed on concentric rings such that γ-rays are focused into a common focal spot by Bragg-reflection in Laue geometry

Ge detectors placed at its focus. In June 2001, the instrument was flown on a stratospheric balloon by the French Space Agency CNES (see von Ballmoos et al. (2004a)). CLAIRE was also tested on a long optical bench that was set up at an aerodrome near Figueres, Spain (Alvarez web-TGD (2003)). Both experiments successfully demonstrated the working principle of the γ-ray lens. For more information about CLAIRE, please refer to Halloin et al. (2004a) and Halloin (2004b).

2.2. The MAX mission

The MAX mission concept proposes a space-borne crystal diffraction telescope (von Ballmoos et al. (2004b),web-MAX (2003)), featuring a Laue lens able to focus in two energy bands, relevant for nuclear astrophysics (450-540 [keV] and 800-920[keV]). Two rings assemblies (an outer ring with Ge crystals and an inner one with Cu crystals) would focus the photons into a small detector placed in a spacecraft flying in formation with the lens spacecraft.

3. EXPERIMENTAL PROPOSALS FOR THE GAMMA-RAY LINE BEAM

3.1. Measurement of diffraction efficiencies in mosaic crystals

The precise measurement of the diffraction efficiency of mosaic crystals is essential to determine the main properties of the gamma-ray lens telescope, i.e., effective area, field of view and energy bandpass. The first measurements of diffraction efficiencies of Ge mosaic crystals (10mmx10mm) in the energy range from 200 to 500 keV were made at the Advanced Photon

Source synchrotron (APS) at Argonne National Laboratory (Köhnle et al. (1998)). These measurements allowed to perform a detailed study about diffraction efficiency in the [111] and [220] crystalline planes ([ijk] are the Miller indices). Second and third order diffraction efficiencies ([440] and [333] planes) were also measured, as well as the dependency of diffraction efficiency on *mosaic width* (as defined in the Darwin model of mosaic crystals). A Monte Carlo simulation ray-tracing program based on the Darwin model of the mosaic crystals was written in order to model these results. General agreement was found between the model and the experimental measurements; therefore, first determination of γ-ray lens performance were possible (Köhnle et al. (1998))

The gamma-ray beam line (GRL) would allow to repeat the measurements performed at the Advanced Photon Source synchrotron in other energy ranges and with other crystals (Cu or Si). Both the measurements in other energy ranges (0.5 to 1.5 MeV) and with other crystals are an essential step for the development of the future project MAX.

A free electron laser (FEL) would be needed to perform the required measurements, at energies $\sim$ 1 MeV. The FEL would permit to tune the maximum gamma-ray energy got through backscattering, in order to maximize the number of photons at low energies ($\sim$ 1 MeV). In such a way, the gamma-ray beam obtained would be very well suited to study the diffraction process in the crystals. If a standard CO_2 laser were used, the spectrum would be essentially flat, with maximum energy around 10 MeV. Then, a similar procedure to that used in APS could be adopted to get a particular energy: one crystal would act as monochromator and the beam diffracted by this crystal would be the incident beam on the crystal under study.

In any case, the gamma-ray line would be much more convenient for the determination of diffraction efficiencies and crystal characteristics than synchrotron radiation used before at APS because it would provide

- more flux at the energy of interest($\sim$ 1MeV)
- strong collimation (similar to that of an astronomical point source)

All these factors ensure that the future GRL would be a tremendously useful tool to characterize the mosaic crystals and to measure their diffraction efficiencies.

3.2. Tuning the crystals of the Laue diffraction lens

Tuning the lens means than each crystal of the lens should be oriented so that the angle between the incident beam and the crystalline plane is the Bragg angle. This orientation of the crystals allows to define the lens focus and the corresponding focal distance, from the Bragg angle and the distance of each crystal to the *optical axis*. Therefore, the focal distance depends on the diffracted energy, because the Bragg diffraction angle depends on it (see equation 1).

The focal distance of the CLAIRE lens is 279 cm for 170 keV, whereas focal distances around 100 m are envisioned for MAX. It is clear that any type of lens able to focus gamma rays has extremely long focal distances, much larger than typical lab sizes. Incidentally, there is another type of gamma-ray lens under study at CESR, the Fresnel lens, which has typical focal distances of 10^6 km, thus needing distances around 500 m at least to perform the scaled tests needed to validate the functioning principle of the lens (Skinner et al. (2003)). In the case of the Laue lens CLAIRE, the long distance test performed in Ordis and the CNES stratospheric balloon flight proved that the tuning of the lens can be performed at a distance shorter than the focal length provided that the energy of the photons is scaled accordingly (see above, section 2.1). An alternative way to reduce the focal length without reducing the diffracted energy would be to use second and third diffraction orders. Despite the decreasing diffraction efficiency as reflection order increases, a large incoming flux as expected in the GRL would permit such type of measurements. This would allow for the tuning of the whole lens, a very important step indeed, to guarantee the performance of the lens.

3.3. Other calibrations

Another important application of the GRL would be the calibration of detectors. The GRL would provide an excellent photon source that would make possible to measure the capability to detect polarization, in addition to the standard sensitivity of the detector.

There is a previous experience of a GRL used to calibrate an instrument, based on the Compton scattering technique to detect gamma-rays in the MeV energy range. This was the Medium Energy Gamma-ray Astronomy (MEGA) instrument, in the 400 keV - 50 MeV range, successfully calibrated at HIGS (High Intensity Gamma-ray Source), in Durham, USA (Andritschke, R..et al. (2004)).

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X-Ray Polarimetry Workshop, SLAC, Stanford, California 9-11 February 2004: http://heasarc.gsfc.nasa.gov/docs/heasarc/polar/polar.html