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A Scintillator-Based Hard X-Ray Imaging Telescope -- CASTER

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The primary scientific goal of the Black Hole Finder Probe (BHFP) mission, a component of the NASA Beyond Einstein program, is to survey the local Universe for black holes over a wide range of mass and accretion rate. One approach to such a survey is a hard X-ray coded aperture imaging telescope operating in the 10 - 600 keV energy band, a spectral range especially useful for detecting black hole sources and studying their spectra. The development of new inorganic scintillator materials (e.g., $LaBr_3$ and $LaCl_3$) provides improved energy resolution and timing performance that is well suited to the BHFP science requirements. Detection planes formed with such materials coupled with a new generation of readout devices represent a significant advance in the performance capabilities of scintillator-based gamma cameras. We discuss the Coded Aperture Survey Telescope for Energetic Radiation (CASTER), a mission concept for a BHFP based on the use of the latest scintillator technology, and present laboratory test results demonstrating the expected scintillator performance.

1. Introduction

As part of NASA's Beyond Einstein program, the Black Hole Finder Probe (BHFP) is designed to survey the local Universe for black holes over a wide range of mass and accretion rate. One approach to such a survey is a hard X-ray coded aperture imaging mission operating in the 10 - 600 keV energy band. The large detector area, high sensitivity, and directional resolution required for such a mission can be achieved at a reasonable cost with inorganic scintillators: New scintillator materials (e.g., $LaCl_3$ and $LaBr_3$) provide improved light output, energy resolution, and timing; new readout devices provide improved capabilities; and the use of segmented scintillators coupled to optical fibers promises to reduce the number of electronics channels and simplify the readout complexity. We describe the Coded Aperture Survey Telescope for Energetic Radiation (CASTER), a mission concept optimized to meet the BHFP science goals using an array of wide-field-of-view coded apertures with detection planes based on inorganic scintillators, and the technology developments that make CASTER possible.

The task of a hard X-ray BHFP mission is to perform an all-sky census of black hole sources with a 1-year 5σ sensitivity level of $F_{\mathrm{lim}} \sim 5 \times 10^{-13}$ erg cm^{-2} s^{-1} (20 -100 keV). This corresponds to ~0.02 mCrab in the 20 -100 keV energy band, a sensitivity level comparable to that of the all-sky survey performed at lower energies (0.5 -2.5 keV) by ROSAT. As currently conceived, the BHFP will provide a hard X-ray survey that is ~1000 × more sensitive than the only previous all-sky survey (HEAO A-4), 1-20 × more sensitive than the all-sky survey of Swift, and ~20 × more sensitive than CGRO/BATSE for γ-ray bursts. Given this sensitivity requirement, an angular resolution of 3 - 5 arcmin is necessary to avoid source confusion from the more than 30,000 AGN that will be detected. This will permit the localization of bright sources with an accuracy of ~10 arcsec. The faintest sources will have ~1 arcmin centroids, sufficient for identification with bright galaxies or as a guide for higher resolution instruments such as Con-X. These scientific objectives can only be met by using a coded aperture imaging instrument. The scientific requirements lead to a set of detector constraints including spatial resolution in 3 dimensions, the ability to resolve multi-hit events, photon detection efficiency, photofraction, and energy resolution. Cost and availability of detector material are important risk considerations.

The detector technology is a crucial driver for the BHFP mission design. Considerable recent attention has been devoted to the development of room temperature solid state spectrometers, in particular cadmium zinc telluride (CZT). CZT detectors promise excellent energy and spatial resolutions, and in principle satisfy the BHFP science requirements. However, given the cost and complexity issues associated with thick, large area CZT, it is prudent to consider alternative detector technologies. This is especially true given that several new experimental techniques are successfully being applied using standard technologies -- inorganic scintillators, wavelength-shifting fibers, and photomultiplier tubes (PMTs), all of which have laboratory and space flight heritage. In particular, recently developed cerium-doped lanthanum chloride ($LaCl_3$) and lanthanum bromide ($LaBr_3$) scintillators provide improved light yield and performance that is well suited to the BHFP science requirements.

2. Implementation Approach

The BHFP science has been described elsewhere[1,2]. The CASTER approach[2] employs an array of wide-field-of-view coded aperture telescopes with detection planes utilizing inorganic scintillators. In order to provide directional resolution on the order of arcminutes, the detector plane must provide ~ 1 mm position resolution; in order to provide sensitivity at the 0.02 mCrab level, the detector area must be ~ 5 m^2; and in order to provide sensitivity at 511 keV, the detector thickness must be ~ 1 cm of scintillator or CZT and the mask must have a thickness of 0.5 – 1 cm of tungsten. The CASTER detector plane will consist of a layer of scintillator read out in either a gamma camera or optical fiber mode. We concentrate here on the fiber mode. An array of ~ 38 × 38 cm^2 × 1 cm thick CsI, $LaCl_3$, or $LaBr_3$ forms the basic X-ray detector. In the case of CsI, a 1 cm thick scintillator absorbs ~ 35% of incident 511 keV photons, with 20% of the cross section due to photoelectric absorption. The CsI(Na) light output peaks near 420 nm. A layer of 189 2 mm square, double clad waveshifting fibers is laid in the x-direction across the top of the CsI layer (separated from the CsI by a thin glass seal that provides a moisture barrier), and a second layer of fibers is laid in the y-direction across the bottom (Fig. 1). With an absorption peak also near 420 nm, the fibers effectively absorb the scintillation light and re-emit a portion of it down the fiber axis with the peak of the emission spectrum near 490 nm. The light is viewed at the ends of the fibers by a set of 3 64-channel multi-anode photomultiplier tubes (e.g., Hamamatsu R5900-M64 or Burle Planacons). The crossed fiber layers are intended to measure x- and y-position only. Only a small fraction of the light is trapped in the fibers. Most of the light escapes the fibers. The energy measurement, therefore, is performed by a set of nine large “energy measuring” PMTs (130 mm Electron Tubes 9390KB) viewing the scintillator through the bottom fiber layer and a set of light pipes.

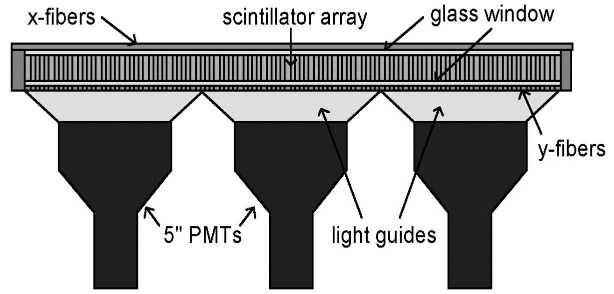

Figure 1. Detector plane element consisting of scintillator (in this case a segmented CsI array of 2 x 2 mm^2 pixels produced by St. Gobain Crystals and Detectors) read out by crossed wavelength-shifting fiber arrays and multi-anode PMTs (not shown). The fibers are used for position determination. The large area PMTs are used for measuring total energy deposit.

3. Lanthanum Bromide and Lanthanum Chloride Scintillator: Measured Results

In order to detect X-rays efficiently in a single fiber, the light output must be maximized and the fiber absorption spectrum must be matched to the scintillator output. Three potential scintillator materials are CsI(Na), $LaCl_3$, and $LaBr_3$. Their key features are listed in Table 1, along with those of other materials commonly used for hard X- and γ-ray detection. The light output of $LaBr_3$ doped with 0.5% Ce, in particular, is ~60,000 photons/MeV[3], among the highest values for inorganic scintillators. In addition, the proportionality as a function of energy also contributes to the resolution. This is important if multiple Compton interactions occur before the energy is fully absorbed. Over the range 60 - 1275 keV, the non-proportionality in light yield is ~6% for $LaBr_3$ compared to ~20% for NaI(Tl) and CsI(Tl)[4]. With its higher proportionality and higher light output, $LaBr_3$ provides better resolution than any other scintillator. Finally, the spectra of CsI(Na), $LaCl_3$, and $LaBr_3$ are well matched to St. Gobain waveshifting fibers BCF 91A, BCF 99-90, and BCF 99-33A, which have absorption spectra with peak wavelengths 420, 345, and 375 nm respectively.

Table 1. Summary of Detector Characteristics

	$LaBr_3$	**$LaCl_3$**	**CsI(Na)**	**CsI(Tl)**	**NaI(Tl)**	**BGO**	**CZT**	**Ge**
Density (g/cm^3)	5.29	3.86	4.51	4.51	3.67	7.13	5.78	5.33
Light Output (ph/MeV)	63,000	49,000	39,000	52,000	39,000	9000	N/A	N/A
dE/E(FWHM) @ 662 keV	<3%	3.5%	7.5%	10%	7%	>10%	<3%	0.3%
Peak l (nm)	358-385	330-352	420	550	415	480	N/A	N/A
Fast Decay (ns)	25	25	630	1000	230	300	N/A	N/A
Hygroscopic	yes	Yes	yes	slightly	yes	no	no	no
Cost (per cm^3)	$30	$30	$4.50	$4.50	$2	$9	$3000	$500

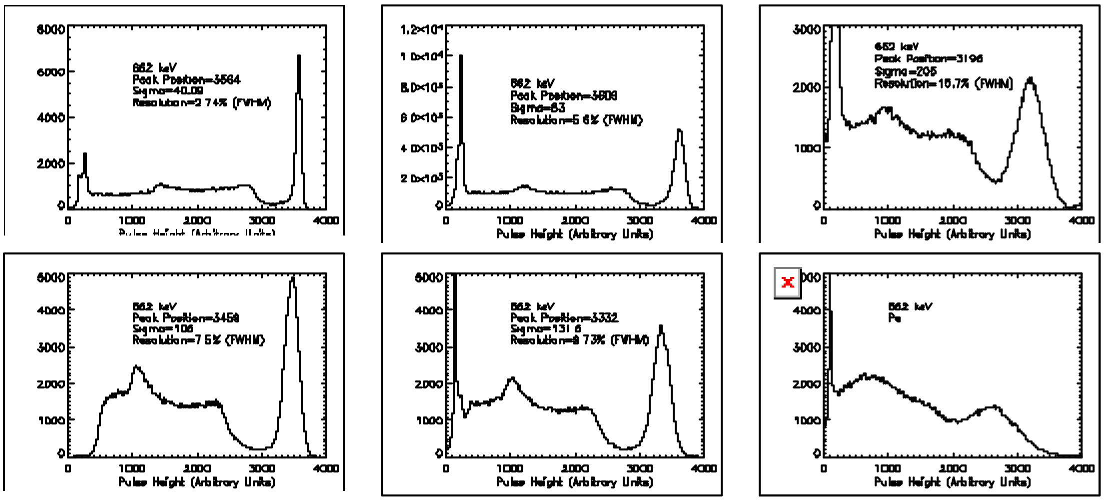

Figure 2a-c (top, left to right): $LaBr_3$ viewed directly, in the energy PMT, and at the end of a 2 mm fiber, as described in the text. **Figure 3a-c** (bottom, left to right): Similar for NaI(Tl).

Fig. 2a shows the spectrum of a ^{137}Cs source obtained with a 2.5 cm diameter × 2.5 cm thick $LaBr_3$ detector at room temperature. The energy resolution at 662 keV is 2.7% FWHM, comparable to the quoted resolution

(3%) for off-the-shelf spectroscopy grade CZT from eV Products (http://www.evproducts.com). The high $LaBr_3$ signal level will permit lower energy thresholds than possible with other scintillators. Although not optimized for low energy response, note that the 32 keV line in the spectrum is visible as well. Fig. 2b shows the spectrum in the energy-measuring tubes viewed through a layer of 2 mm St. Gobain BCF 99-33A fibers; the 662 keV resolution is still 5.6%. Finally, Fig. 2c shows the spectrum viewed at the end of a fiber, with resolution 16%. The response has been measured for a variety of sources from 32 to 662 keV, with linearity observed to be better than 2% and a measured yield through a single fiber of ~25 keV/photoelectron. For comparison, spectra are shown for NaI(Tl) in Figs. 3a-c. In the same geometry as above, NaI viewed directly gives a FWHM of 7.5%; viewed in the energy tube through a layer of 2 mm fibers, the resolution deteriorates to 9.7%; and viewed at the end of the fibers, the observed 662 keV resolution is 32%, corresponding to ~170 keV/photoelectron. The $LaCl_3$ resolution is measured to be intermediate between NaI and $LaBr_3$: 4.1%, 9.4%, and 20.3% for the same three configurations.

4. Conclusions

The ability to fabricate lanthanum halides in large volumes offers improved detection efficiency at relatively high energies. Several manufacturers are currently growing both $LaCl_3$ and $LaBr_3$ crystals using proprietary processes. No fundamental barriers have been identified that would prevent crystal growth and detector fabrication with volumes as large as are presently possible for NaI. Early measurements are promising. We are currently planning a series of radiation damage and activation measurements, preparing to construct a 40×40 cm^2 prototype of a CASTER imaging element, and carrying out a detailed mission study to optimize the design of a scintillator-based BHFP instrument and understand its expected capabilities and performance in detail.

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