Proposed (to) EXIST: Hard X-ray Imaging All Sky Survey/Monitor

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Abstract

The hard x-ray (10-600 keV) sky is inherently time variable and yet has neither been surveyed nor been monitored with a sensitive imaging telescope. The Energetic X-ray Imaging Survey Telescope (EXIST) is a mission concept, proposed for MIDEX, which would conduct the first imaging all-sky hard x-ray survey as well as provide a sensitive all sky monitor (ASM). With ~60% sky coverage each orbit, and full sky coverage each ~50 days, hard x-ray studies of gamma-ray bursts, AGN, galactic transients, x-ray binaries and accretion-powered pulsars can be conducted over a wide range of timescales. We summarize the scientific objectives of EXIST for both the survey and monitoring objectives. We describe the mission concept and the instrumentation approach, which incorporates a large area array of Cd-Zn-Te (CZT) detectors, as well as some of our ongoing development of CZT array detectors.

Key words: surveys: X-rays — X-ray sources: binaries, black holes, AGN — GRBs — instruments: all sky monitors

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1. Introduction

The Energetic X-ray Imaging Survey Telescope (EXIST) was proposed (in December 1994) and accepted (April 1995) as one of the 27 New Mission Concept (NMC) studies for a satellite-borne astrophysics mission. It would conduct the first imaging survey of the sky at hard x-ray energies (10-600 keV) with a sensitivity some 100× greater than the only previous all-sky survey carried out by HEAO-A4 experiment in 1978-80 (Levine et al 1984). The need, and priority, for such an all sky imaging hard x-ray survey mission has been pointed out in the recent report of the NASA Gamma-Ray Program Working Group. An overall description of the initial EXIST concept is given by Grindlay et al (1995) (and on the Web site *http://hea-www.harvard.edu/EXIST/EXIST.html*). EXIST has been developed extensively in the course of preparation and submission of a successful "Step 1" and invited (1995) "Step 2" proposal for the MIDEX program. The mission is being further developed for the next MIDEX solicitation, including additional laboratory development and balloon flight testing of the Cd-Zn-Te detectors proposed, and community input for the mission design has been sought. A detailed summary and description of the Mission Concept Study will be given by Grindlay et al (1997).

2. Overview of EXIST

A survey telescope at hard x-ray energies can be constructed as a coded aperture telescope with a field of view of up to ~45° without significant projection effects or collimation by the mask aperture, assumed planar. Such a telescope would execute a continuous scan rather than fixed target pointing to cover a maximum sky fraction in minimum time and would be more sensitive (above 30 keV) than a scanning grazing incidence (multi-layer) telescope of comparable (or even larger)

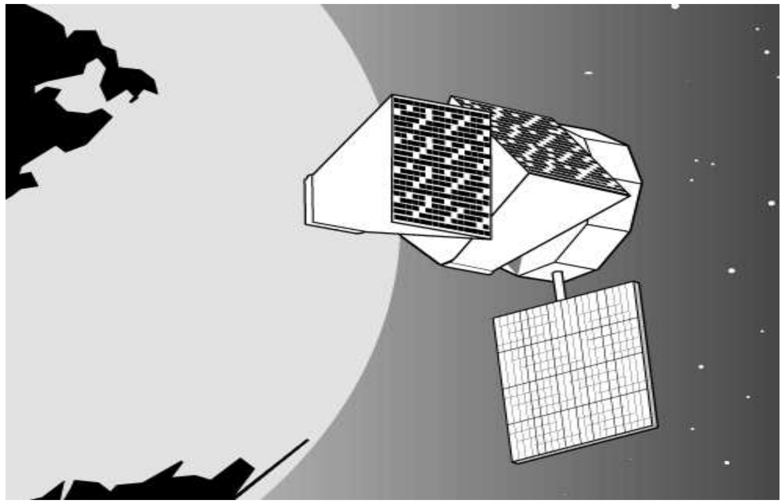

Fig. 1. Schematic view of EXIST in orbit showing layout of coded aperture telescopes and spacecraft.

physical size though smaller effective area and field of view. For example, a multi-layer telescope with (currently ambitious) parameters of FOV $\sim 10'$ and effective area $A_{eff} \sim 500 \text{cm}^2$ in a scanning (ROSAT-like) satellite mission would be a factor of $\sim$10 *less* sensitive than a wide-field (FOV $\sim$ 20-40°) scanning coded aperture telescope with $A_{eff} \sim 5000$ cm^2 in the 30-100 keV band. In addition, the wide-field coded aperture imager allows the survey to extend up to the poorly explored 100-600 keV range, totally unaccessible to focussing optics (except for Bragg concentrators, which can work only in a very narrow energy band).

EXIST would incorporate two coded aperture telescopes, each with FOV = 40° × 40° (above $\sim$40 keV; at 10-30 keV a low energy collimator would restrict the FOV to 3.5° in one dimension), for a combined FOV = 40° × 80° ,. A Cd-Zn-Te (CZT) detector array of total area of 2500 cm^2 is at the focal plane of each telescope. The schematic layout of the two telescopes and a possible spacecraft implementation is shown in Figure 1.

Because of its very large FOV and large area detectors with high intrinsic resolution (both spatial and spectral), EXIST could approach the unprecedented all-sky sensitivity shown in Figure 2. The sensitivity plots are for EXIST for its proposed 9-month all-sky survey (followed by a pointed mission phase), which would allow total integration times of $\sim 10^6$ sec for any source.

Although the mission is designed primarily as a survey and monitor mission, it could be operated as a pointed (observatory) mission for selected high priority targets and very long exposure times (e.g. M31 GRB and BHC surveys; galactic bulge survey) in which case even greater total exposure times and thus sensitivities can be achieved.

3. Scientific Objectives: All Sky Survey and Monitoring

The scientific objectives for the EXIST mission may be summarized either by classes of object to be studied or by the broad objectives of surveys and monitoring studies. In this paper we emphasize the monitoring and general time-variability studies that EXIST can carry out. However, since many of these require the hard x-ray samples and populations of (many) classes of object to be first studied and established beyond the currently limited samples, we begin with the survey objectives.

3.1. Surveys

Hard x-ray spectra and luminosity function of AGNs: Active galactic nuclei (AGN) are now measured by OSSE to have hard spectra with breaks typically in the 50-100 keV range for Seyferts (cf. Zdjiarski et al 1995) and with multi-component or non-thermal spectra extending to higher energies likely for the blazars. EXIST will have an all-sky sensitivity some 10× better than that needed to detect the "typical" Seyferts seen with OSSE. More than 1000 AGN should be detected in the all sky survey and EXIST has the required sensitivity in the poorly explored 30-200 keV band to measure accurate spectra for all known AGN detected with Ginga or with the Einstein slew survey.

A major objective for AGN studies and surveys is the detection and inventory of heavily obscured or self-absorbed AGN. Such objects, primarily Seyfert 2's but also including (some) star-formation galaxies, are now

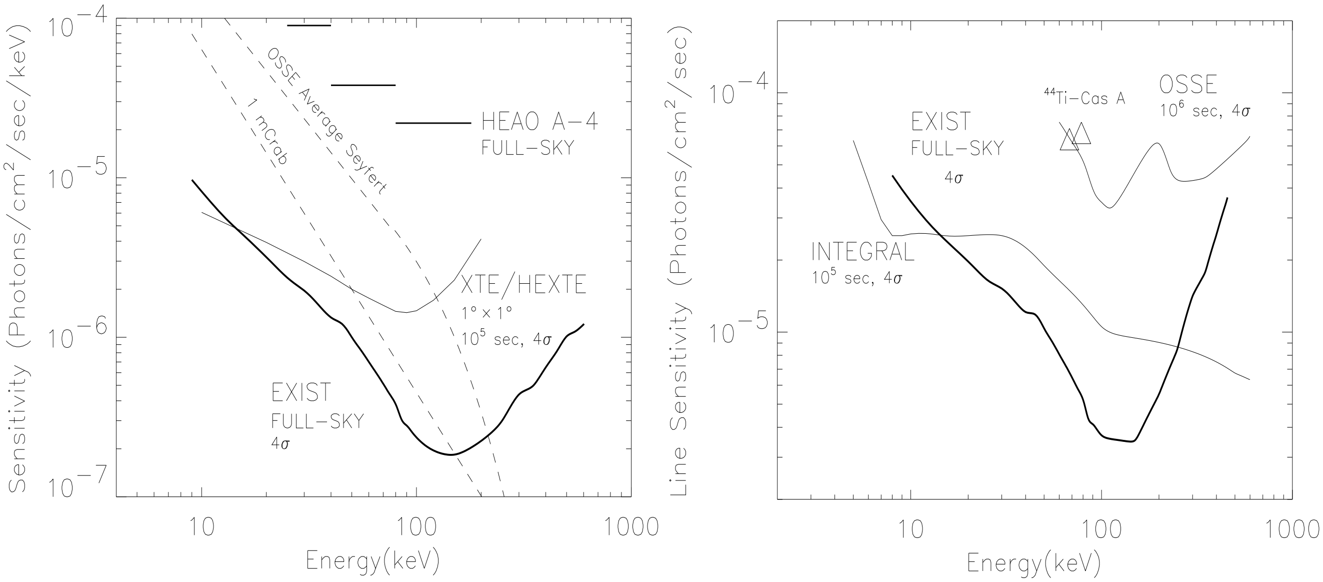

Fig. 2. Sensitivity of EXIST (MIDEX) for continuum (left) and narrow line (right) spectra and compared with other missions.

being discovered in pointed observations with SAX (cf. Piro, these proceedings) and will also likely be discovered with the focussing ABRIXAS all sky survey up to $\sim$10 keV(cf. Staubert, these proceedings). However, the most heavily obscured objects, with absorbing column densities $\gtrsim 10^{24-25}\mathrm{cm}^{-2}$ yielding low energy cutoffs in the 5-10 keV range, will be more readily detected with EXIST. This, together with the EXIST measure of the hard spectra and thus total luminosity of the still larger sample of obscured AGN with lower cutoffs discovered with comparable sensitivity ($\sim$0.1mCrab) with ABRIXAS, will yield the first measure of the luminosity function of this important yet poorly studied class of AGN.

Survey for black hole and neutron star compact binaries. Studies of compact objects over a wide range of timescales and luminosity are possible throughout the Galaxy. A deep galactic survey for x-ray binaries containing black holes vs. neutron stars and pulsars will allow the relative populations of black holes in the Galaxy to be constrained. All previous galactic hard x-ray surveys have been constrained to the brightest decade in source flux (and luminosity); EXIST will extend this 1-2 decades deeper. Whereas the INTEGRAL galactic plane survey(s) will also make great strides, the EXIST (all sky) survey will be more sensitive and not be limited to the central $\sim \pm 7°$ of galactic latitude covered by the smaller FOV of INTEGRAL. The EXIST survey will also sample the galactic plane on a wider range of timescales.

Emission line surveys: hidden supernovae via ^{44}Ti emission and 511 keV sources: The array of CZT imaging detectors proposed for EXIST achieves high spectral resolution (e.g. $\sim$5% at 60 keV). Thus emission line surveys can be conducted. The decay of ^{44}Ti (lines at 68 and 78 keV) with long (68 y) halflife allows a search for the long-sought population of obscured supernovae in the galactic plane at sensitivities significantly better than the possible detection of Cas-A (cf. Figure 2). These objects would likely appear as discrete (unresolved) emission line sources. Similarly, 511 keV emission from black hole binaries (or AGN) can be searched for (e.g. in transient outbursts), and the diffuse galactic 511 keV emission imaged with sensitivity comparable to OSSE (cf. Figure 2).

Study of the diffuse hard x-ray background: The spectra of a significant sample of AGN will test the AGN origin of the diffuse background for the poorly explored hard x-ray band. Because the background measured by the EXIST detectors below 100 keV is dominated by the cosmic diffuse spectrum, its isotropy and fluctuation spectrum can be studied with much higher sensitivity than before.

3.2. Monitoring

EXIST surveys 60% of the sky each day, yielding $\sim$10 orbits/day (allowing for SAA, etc.) $\times \gtrsim 10$ min exposure/orbit or $\gtrsim 6000$ sec/day for each source observed. This yields a daily flux sensitivity (30-100 keV) of $\sim$1-2 mCrab, sufficient for the brightest AGN and essentially all known accretion-powered binaries in the Galaxy. Pulsar timing allows even fainter flux limits, as demonstrated with the extensive BATSE monitoring project (cf. Bildsten et al 1997). Over one sky survey epoch ($\sim$50d), each source is observed for $\gtrsim$ 25d, and variability flux limits for $\sim$month timescales are thus

$\sim$0.3mCrab.

Faint hard x-ray transients: black hole population in Galaxy: The sensitivity to $\sim$1-10d transients is $\gtrsim 30 \times$ better than BATSE, so that the low resolution occulatation-imaging survey for faint transients being conducted with BATSE (cf. Grindlay et al 1996) can be extended to correspondingly lower outburst luminosities or greater source distances. With a 1-10d sensitivity of only $\sim$1 mCrab, BH transients can be detected with their characteristic peak luminosities of $\sim 10^{37-38}$erg/s (10-100 keV) out to 100 kpc, so that the LMC/SMC can be surveyed in hard x-rays for the first time. Since the transients containing BHs are characterized by hard x-ray spectral components (extending usually to $\gtrsim 100$ keV) which are both more luminous (at peak) and longer lived than than the hard tails found for NS systems, the hard x-ray all-sky survey provides perhaps the best strategy for discovering x-ray binaries containing BHs.

Monitoring and Study of X-ray Pulsars: The measurement and monitoring of spin periods, pulse shapes and luminosity/spectra of a large sample of accretion-powered pulsars would extend the BATSE sample of Bildsten et al (1997) to the entire sample ($\gtrsim 30$) of known accretion-powered pulsars. The high spectral resolution of the CZT detectors on EXIST will allow high sensitivity studies of cyclotron features in pulsar spectra, greatly extending current RXTE/HEXTE studies of relatively few objects to a much larger sample.

Studies of Gamma-ray Bursts: EXIST would have a GRB sensitivity approximately 20$\times$ that of BATSE so that a 2 month pointed exposure could both detect and map a halo in the Andromeda galaxy (M31) should one exist as a component of the GRB population. Given the observed GRB logN-logS relation, EXIST should detect GRBs overall at about 1/2 the rate, or $\sim$0.5/day, as BATSE with its much larger FOV but reduced sensitivity. GRBs will be located to $\lesssim 1\text{-}5'$ positions, thereby providing definitive tests of repeaters. Bright burst positions and spectra could be brought down in real time for automated followup searches.

4. Detector, Telescope and Overall Mission Concepts

4.1. Detector Concept

The sensitivity and resolution (both angular and spectral) desired for EXIST can be achieved with a large area array of pixellated CZT detectors used as the position-sensitive readout for a wide-field coded aperture telescope. The wide-field needed for the monitoring as well as survey objectives, combined with the desired sensitivity up to $\sim$600 keV, lead to a relatively thick (3-5mm, minimum) detector with moderately large pixel size. For the 40° FOV, and a 5mm thick detector, the pixels need be $\gtrsim$ 5mm $\times$ tan(20°) $\sim$ 1.9mm across for minimal charge spreading due to projection effects. Since CZT crystals are much more readily available (currently, at least) in $\lesssim$ 10-12mm crystal sizes, this leads naturally to a unit detector element of 12 mm (square) $\times$ 5mm (thick) on which a 4 $\times$ 4 array of 2.5mm (square) pixels is inscribed with 0.5mm gaps between pixels. Such a detector pixel size/thickness ratio should yield a reasonable small pixel effect advantage (cf. Barret et al 1995), and studies are currently underway by us (at CfA) to verify this.

The individual 4 $\times$ 4 pixel detector elements would be grouped into a 2 $\times$ 2 sub-array for a 64-channel basic detector element (BDE) read out by a preamp-shaper-multiplexer ASIC readout circuit with very low power dissipation) $\lesssim$ 1mW/channel). The ASIC is self-triggered and multiplexes its 64-channel output to a processing chain which could encode the 1, 4, or 16 peak channels (configured on command) so that multi-site detection (e.g. Compton events and internal background rejection) could be accomplished. We are currently investigating packaging schemes to assemble these unit detector elements (BDE) into a tiled array. It is likely that tiling would be done by combining a sub-array of 4 $\times$ 4 BDEs contiguously into a single basic detector module (BDM), with area $\sim$100 cm^2 (depending on final choice of unit detector and thus also pixel size).

The 40° collimator could be either passive (e.g. Ta slats) or, more effective, active (BGO). We are studying the tradeoffs but an active collimator would allow each BDM to be separately shielded with a rear (2cm)/side (0.5-1cm) BGO shield for a well-type geometry yielding both collimation and lower background (due to forward-hemisphere rejection of internal CZT activation background as well as lack of production in the passive collimator). For the 40° (FWHM) field of view desired for each EXIST telescope, the BGO shield/collimator blade height is 12cm so that the BDM modules are nearly cubic. Each of the two complete EXIST detectors would thus consist of an array of 5 $\times$ 5 or 25 such BDMs. These modules would be close-packed and mounted in a common frame. Although the collimator shields will require a net gap of $\sim$1.5 cm between each of the 5 BDMs across the detector array, this does not affect image reconstruction but only makes the detector $\sim$8 cm larger on a side.

4.2. Telescope Concept

The coded aperture telescopes can be relatively compact design with coded mask at focal length 1.4m and mask pixel size 5mm. This yields an imaging resolution of 12$'$, which is appropriate to resolve even the most crowded galactic bulge fields at the high sensitivity expected. In order to cover the full 40° field of view, each telescope would have a URA mask of approximate dimensions 1.2m $\times$ 1.2m and format 257 $\times$ 255 to fully image the 40° FWHM field of view. However, since the BGO collimator on each BDM segment of the detector array would produce partial coding for sources off-axis, the mask must be either smaller format and repeated (e.g. 4 contiguous 129 × 127 masks, leading to ambiguous source positions) or random. A random mask would be, in any case, as effective as a URA of such large format. Since the coded mask should not collimate the image significantly, the mask thickness is restricted to be $\lesssim$ 5mm, which (for Ta mask elements) restricts its upper energy limit to be $\lesssim$ 600 keV for partial shadowing.

4.3. Mission Concept

EXIST is proposed as a MIDEX with nominal lifetime of 2 years (although with no consumables, an extended mission is desirable). The baseline plan is for the all sky survey to be conducted in the first 10 months (including a 1 month verification phase) which allows 6 passes through the sky. The entire sky is then effectively surveyed to a total exposure of $\sim 1.5 \times 10^6$ sec for any source. The two-telescope combined FOV of 80° is pointed North-South, and the pointing direction "nods" toward the poles during the high latitude portion of the orbit so that all-sky coverage is uniform over the survey to within $\lesssim$ 10%. A pointed mission phase of 2 months within the first year would allow the deep survey of M31 (for GRBs and BHCs) and the galactic center and/or the LMC/SMC to be conducted (during M31 occultations). These deep pointed surveys would more than double the total exposure on these targets that has been acquired during the all sky survey phase, as well as allow for broader timescales of coverage. The second year of the nominal mission would be a pointed phase, with a series of deep pointings (~1 month each) designed to both allow deep surveys and TOOs as well as to effectively extend the all sky survey and ASM function given the large FOV covered. Data from the entire mission is open (by proposal) to the entire community, and pointing directions/durations (and surveys) are proposed by a GI program.

5. Ongoing CZT and Array Studies

As part of the effort to both conduct the EXIST Mission Concept study and optimize the design for a future MIDEX proposal as well as a prototype balloon-borne implementation, we are conducting a variety of studies of CZT detectors and array technologies at our respective institutions. Here we outline briefly the projects underway at CfA; space does not permit description of the significant development efforts underway at the other institutions in the EXIST collaboration.

Balloon Flight Tests of Backgrounds and Shielding Efficiency: The large neutron cross section(s) for Cd, which result in prompt gamma-ray decays, may yield high internal backgrounds for CZT detectors in space. Balloon flight tests of single isolated CZT detectors by the GSFC and Caltech groups in May and September-October, 1995, suggested disturbingly large in-flight backgrounds compared to those expected for similar scintillation detectors (e.g. Parsons et al 1996). However the GSFC measurement of a marked reduction in background with an external anti-coincidence shield (NaI) suggested this could be effectively reduced by suitable active shielding.

In collaboration with Caltech and JPL, we assembled a flight unit to test the prompt anti-coincidence shielding efficiency of a planar BGO shield immediately behind the CZT detector plane, as proposed originally for EXIST (a future experiment will test the possible well-type geometry). The BGO (75mm diameter × 75mm thick, and supplied by JPL) was centered below a single element CZT detector (10mm × 10mm × 2mm, and supplied by eV Products to Caltech). The detector-shield and preamp was mounted in a pressure vessel and shielded with a 1.8mm thick Pb + 0.8mm thick Sn and 1.2mm Cu graded shield to simulate the approximate grammage of the passive high energy collimator in the baseline EXIST detector. The raw CZT and BGO (shield) detector preamp outputs are interfaced to shaping amps and digital (discriminator and 12 bit ADC) electronics built at CfA to interface to the flight computer and data system for the EXITE2 balloon-borne telescope (Lum et al 1994, 1997).

A balloon flight was (finally) obtained on May 8, 1997. The background spectrum in the CZT is reduced by a factor (energy-dependent) of ~4-8 with the BGO veto and is at flux level at 100 keV of $\sim 1.0 \times 10^{-3}$ cts/ cm^2-sec, or within a factor of 2 of the EXITE2 phoswich background level measured simultaneously. With the additional shielding efficiency possible with a well-type active BGO collimator, the background may be reduced another factor of ~2. Full details are given in Bloser et al (1997).

Balloon Flight Measure of Neutron Backgrounds: In order to fully calibrate the CZT background and shielding experiment so that balloon results may be extrapolated to the full space environment, a simultaneous measure of the neutron flux experienced by the detector is desirable. The atmospheric neutron fluxes as tabulated by Armstrong et al (1973) are sufficiently uncertain (probably by a factor of $\gtrsim$ 2) that we have attempted to measure the flux by a simple passive experiment: an array (7 × 6) of gold foils (each ~6cm^2) mounted on top of the gondola in which the n-γ reaction

Au-197(n,γ) $\rightarrow$ Au-198(,e)Hg-198

was (attempted to be) measured after the flight by observing the resulting 412 keV decay γ-ray (2.7d halflife) with a low background Ge spectrometer at JPL (by L. Varnell). This experiment, conducted in collaboration with G. Skinner and L. Varnell, is currently being analyzed.

Spatial Uniformity of CZT: Pixellated CZT detector arrays, as proposed for EXIST, will require relatively uniform response across both the projected surface area and depth of the detector elements. Non-uniformities of detector response can be calibrated out (by flat fielding) but will be simplified to the extent the detectors are uniform (and may be less of a problem with the relatively large pixel detectors for EXIST than with small pixel CZT imagers for focussing optics). We have conducted a program of mapping the spectral response of single detectors and comparing the observed variations with IR micrographs (obtained at eV Products) of the detector to correlate spectral response with grain boundaries and inclusions in the detector. Spectra (Am-241) obtained in a 3 $\times$ 3 raster scan of a 0.5mm beam across a 4mm $\times$ 4mm $\times$ 3mm CZT detector show variation in spectral response which correlates with the grain boundaries as well as inclusions and precipitates. Results were presented at the NASA-SEUS Workshop in December 1996.

Development of PIN Readouts for CZT Detectors: CZT detectors are conventionally fabricated with metal (gold) contacts deposited directly on the CZT crystal. These metal-semiconductor-metal (M-S-M) detectors are of course the subject of intense development and are baselined for EXIST. However, they can suffer from limitations of charge collection efficiency (though at least partially overcome with "small pixel" electrodes; cf. Barrett et al 1995) and poor ohmic contacts. Several groups, most recently SBRC (Hamilton et al 1996) have investigated alternative readouts incorporating P-I-N junctions. The Spire Corp. (Bedford, MA) has developed a new method for fabrication of P-I-N electrodes on CZT by using CdS(p-type) and ZnTe(n-type) layers deposited by thermal evaporation on both high pressure Bridgman (HPB) CZT crystals (from eV Products) as well as lower cost vertical Bridgman (VB) crystals (from Cleveland Crystals), and the results appear very encouraging. A P-I-N configuration for CZT offers the possibilities of both further enhanced energy resolution (due to the higher bias voltage possible) and/or lower detector element cost (due to lower resistivity CZT being possible). At CfA we are testing these P-I-N readout CZT detectors which offer advantages of improved charge collection and ease of fabrication for their use as thick detectors. We are working with Spire to fabricate a 4 $\times$ 4 array P-I-N detector and comparison M-S-M array detector on 10mm $\times$ 10mm $\times$ 5mm CZT substrates for laboratory evaluation and balloon flight tests of background and uniformity of response.

Development of Thick CZT Detector Array Readouts: Thick detectors (5mm or greater) as desired for EXIST pose special challenges for the optimum design of the detector and readout. In particular, the electric field configuration needed for the small pixel effect (Barrett et al 1995) must be carefully considered, and the effects of charge diffusion and spreading become more important. We are exploring these effects in collaboration with both Spire Corp. and the RMD Corporation (Watertown, MA), who have just completed fabrication of a prototype 4 $\times$ 4 array M-S-M detector on a 10mm $\times$ 10mm $\times$ 5mm CZT substrate. Initial results appear very promising and will be reported in Shah et al (1997). At CfA, we are now testing this array for its small-pixel effect properties and we have developed an interface to a 16-channel ASIC preamp/shaper supplied by the IDE Corp (Oslo). The CZT array detectors (10mm; 16 channels) are mounted on chip carriers for easy plug-in intercomparison of the M-S-M vs. P-I-N detectors through the same ASIC readout system, with results presented in a forthcoming paper by Bloser et al (1997). A balloon flight test of both array detectors, with a well-type BGO shield, may be conducted in 1998.

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