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Scintillating Fibers and Their Use in the Cosmic Ray Isotope Spectrometer (CRIS) on the Advanced Composition Explorer (ACE)

W.R. Binns¹, E.R. Christian³, W.R. Cook², A.C. Cummings², B.L. Dougherty⁴, P.F. Dowkontt¹, J.E. Epstein¹, P.L. Hink¹, B. Kecman², J. Klarmann¹, R.A. Leske², M. Lijowski², R.A. Mewaldt², M.A. Olevitch¹, T.T. von Rosenvinge³, E.C. Stone², M.R. Thayer², and M.E. Wiedenbeck⁴

¹Washington University, Campus Box 1105, 1 Brookings Drive, St. Louis, MO 63130
²California Institute of Technology, Mail Code 220-47, Pasadena, CA 91125
³Goddard Space Flight Center, Code 661, Greenbelt, MD 20771
⁴Jet Propulsion Laboratory, Pasadena, CA 91109

Abstract. The Cosmic Ray Isotope Spectrometer (CRIS) experiment was launched aboard the NASA Advanced Composition Explorer satellite on August 25, 1997. The experimental objective of CRIS is to measure the isotopic composition of galactic cosmic ray nuclei for elements with charge 3 ≤ Z ≤ 28 over the energy range ~50-500 MeV/nuc. The instrument consists of a scintillating fiber hodoscope to determine particle trajectory, and four stacks of silicon wafers for multiple dE/dx and Eₘₐₚ measurements. This instrument is the first to use scintillating fibers in space. The CRIS instrument has a large geometrical factor of ~250 cm²sr. The spatial resolution obtained by the fiber hodoscope is ~100 μm. The mass resolution achieved is ~0.12 amu for Carbon and 0.30 amu for the heaviest isotopes measured. Mass histograms of selected isotopes are presented.

INTRODUCTION

The CRIS experiment was launched aboard the NASA Advanced Composition Explorer satellite (1) on August 25, 1997 and is now orbiting about the L1 libration point ~10⁶ miles from Earth along the Earth-Sun line. The experimental objective of CRIS is to measure the isotopic composition of galactic cosmic ray nuclei for elements with charge 3 ≤ Z ≤ 28 over the energy range ~50-500 MeV/nuc. The CRIS geometrical factor is ~250 cm²sr which is more than 20 times larger than previous isotope instruments. This large geometrical factor was made possible in part by the use of a scintillating fiber hodoscope which has considerably larger acceptance geometry than solid state hodoscopes used in previous instruments. This enables us to obtain isotopic abundance measurements with considerably higher statistical precision than has been previously achieved. For some isotopes which are already well measured, the measurements will have reduced statistical uncertainties. However, there are a number of very rare isotopes in this charge range which have not been well measured by previous experiments. For these isotopes, the CRIS measurements will be the first measurements obtained with good statistical precision. In two years of data collection under solar minimum conditions CRIS should collect ~5 x 10⁶ stopping heavy nuclei.
The particles which are detected are predominately cosmic ray nuclei which represent a direct sample of high energy matter originating outside our solar system in the Milky Way galaxy.

There are a variety of issues can be addressed using these measurements. These include:

- Nucleosynthesis of galactic cosmic ray source material.
- Cosmic ray life-times and mean gas density in the galaxy.
- Cosmic ray acceleration time-scales and reacceleration.
- Establish the pattern of isotopic differences between the galactic cosmic rays and solar system matter.
- Compare isotopic patterns in galactic and solar material to test models of galactic evolution.

THE CRIS EXPERIMENT

The CRIS experiment (2) consists of a scintillating optical fiber trajectory (SOFT) detector and four stacks of Lithium drifted Silicon detectors. Each of the four stacks consists of fifteen 3mm thick silicon wafers for multiple $dE/dx$ and $E_{\text{tot}}$ measurements (3). Figure 1 shows cross-sectional views of the CRIS instrument. The SOFT system consists of a hodoscope comprised of three $x,y$ scintillating fiber planes (6 fiber layers) and a trigger detector composed of a single fiber plane (2 fiber layers). The hodoscope and trigger fibers are coupled to an image intensifier which is then coupled to a CCD for hodoscope readout, and to photo-diodes to obtain trigger pulses. The SOFT detector system has two fully redundant readouts, only one of which is operative at any given time because of limited power and bit rate on ACE.

The SOFT Detector

The scintillating fibers consist of a polystyrene core doped with scintillation dyes (BPBD and DPOPOP; emission peak 430nm) and an acrylic cladding (2,4) and are fabricated by Washington University. The fibers have a 200μm square cross-section including a 10μm cladding wall thickness. The cladding of the hodoscope fibers is coated with a black extra-mural absorber (EMA) to prevent cross-talk between fibers. The fibers are bonded together with an elastomeric adhesive (Uralane 5753). Each of the three hodoscope planes is composed of two layers of orthogonally crossed fibers which are bonded to a 25μm thick Kapton substrate. The spacings between the hodoscope planes are 3.9 cm and 3.3 cm as shown in the figure below. The center fiber plane is unequally spaced from the outer planes to enable us to resolve ambiguities in trajectory determination which can occur for low-Z nuclei due to electron "hopping" in the microchannelplate image intensifier. The 26 cm wide hodoscope output for a single fiber layer is split into 11 "tabs" with width ~2.4cm of contiguous fibers. These tabs are stacked and bonded together to form rectangular outputs for each layer with each rectangle having dimensions ~0.3 cm x ~2.4 cm. The two sets of six fiber layer outputs (H1x, H1y, H2x, H2y, H3x, H3y) are each routed to one of the cameras. The six outputs are stacked and held together in a rectangular block. The block is then cut and polished. The output is then coupled to the image intensifier (Figure 2). The trigger fiber plane is essentially identical to the hodoscope planes with the exception that the fibers are not coated with EMA so that we can obtain the maximum light output. The
trigger fiber outputs are formatted in a similar way to the hodoscope fibers as shown in Figure 2. Spacers are placed between the hodoscope and trigger fiber outputs to separate the readout of hodoscope and trigger fibers. Four extra tabs of fibers (not shown) were attached to LEDs and were used for functional testing and alignment checks of the system.

Figure 3 shows a cross-sectional view of the image intensifier assembly. The image intensifiers (5) are 40mm diameter, dual microchannel plate (MCP), gateable devices (Photek Model # MCP-340S) with fiber optic windows on the input and output. The rear MCP is double thickness (0.8 mm) so that the gain of the tube is equivalent to that for a three-MCP intensifier. These tubes have blue peaked, S-20 photocathodes with a sensitivity of ~50-60mA/W at 450nm (roughly 15% quantum efficiency). The intensifiers exhibit about 20 to 30 dark counts/cm²/s at room temperature and a much smaller number at temperatures of ≤0°C (the image intensifier and CCD are passively cooled in space to about -15°C). The output phosphor is P-20
phosphor and a thin film aluminum anode is deposited over the phosphor. The which has a 1/e decay time of about 50 μs, with a low level tail extending for about 1 ms. The output window is coated on the external face with a thin, optically transparent metallic layer which is grounded to eliminate corona from the anode. The tubes are each powered by a high voltage power supply (Model # 2404) made by K&M Electronics (6). The image intensifier was ruggedized so that it could survive the ACE launch vibration and shock levels.

The voltages used to power the intensifier are shown in Figure 3. The cathode voltage with respect to the MCP-in is -200V when it is gated on and +40V when it is gated off. The gating time is ~1μs. The gain of the image intensifier is controlled during flight by adjusting the voltage across the MCPs. The maximum photon gain that can be achieved is ~ 2x10^6 but we are operating at a gain of typically 6x10^5. The image intensifier output which corresponds to the area covered by the hodoscope fibers on the input is coupled onto the large end of a 34.5mm to 11mm (diagonal dimension; 3 to 4 aspect ratio) fiber-optic reducer using Dow-Corning 93-500 adhesive. The reducer output is coupled to a fiber optic window installed on the CCD. The CCD that we are using is a Thomson TH-7866 (244 x 550 pixel array) with individual pixel size 16μm (width) x 27μm (height). A single fiber projects onto an area equivalent to 4 pixels wide by 2.4 pixels high, after the image is reduced by the fiber optic reducer. The output area of the image intensifier which corresponds to the two trigger fiber inputs are

FIGURE 2. The hatched areas show the fiber formatting onto the photocathode of the image intensifier. Additionally, the reducer used to image the intensifier output onto the CCD and the trigger fiber light guides which couple the trigger fibers to the photodiodes are shown.
coupled to Hamamatsu S-3590-01 photodiodes using acrylic light guides. For further details see Reference 2.

FIGURE 3. Side view of image intensified CCD system.

Method of Obtaining Real-Space Coordinates from SOFT

The first step in obtaining real space coordinates is to develop a pixel to fiber map. The left panel of Figure 4 shows a superposition in CCD pixel space of many oxygen events obtained from a MSU NSCL test (7,8). The beam was scanned over the active area so that particles traversed every fiber. Centroids were calculated for each pixel cluster and plotted. The right panel shows a magnified view of a small part of the fiber array. We see that most centroids can be clearly identified with an individual fiber. Cuts were taken through these data in x and y separately along each fiber row and column and the data were histogrammed. The data were then fit with a gaussian fitting routine to obtain the center position of each fiber. From these center positions we defined cells about each position as shown in the right panel. A centroid from an event falling in a given cell is identified with that particular fiber.

The second step is to develop a fiber-space to real-space map. This is obtained using a fiducial hole plate made of lead which has 1 mm diameter holes spaced in a 1.27 cm square grid. The hole plate was placed in an oxygen beam at MSU. Figure 5 shows data from the hole plate fiducial run at MSU. The projection of the holes onto the fiber array is clearly seen. Histograms in x and y were made of each hole and the center of the distribution was taken to be the center of the hole. The application of these two maps enables us to transform from pixel space to real space.
FIGURE 4. Pixel to fiber map. The left panel is a cross plot of pixel cluster centroids in CCD pixel space. This figure is a superposition of many events obtained by scanning an oxygen beam over the full 26cm x 26cm area of the fiber hodoscope. Each row of dots corresponds to a single fiber tab of width ~2.4 cm. The right panel shows an expanded view of a small region in pixel space. It is seen that the individual fibers are clearly resolved as shown in the crossplot and histogram.

FIGURE 5. An absolute calibration of SOFT was obtained by placing a lead mask with regularly spaced holes in the beam and irradiating the hodoscope with oxygen nuclei. The regularly spaced dark spots are the superposition of events which passed through the holes.

SOFT In-Flight Performance

The spatial resolution that is required for SOFT to contribute less than 0.1amu to the mass resolution for iron nuclei at 45° is ~130μm. Figure 6 shows the spatial
resolution obtained for iron nuclei in-flight using the method of residuals. We see that the resolution obtained meets this requirement.

FIGURE 6. Spatial resolution obtained using the method of residuals for x and y coordinates.

FIGURE 7. Histograms of isotope distributions for selected elements from in-flight data.
In Figure 7 we plot mass histograms for a sample of the CRIS data for selected elements. We see that the individual isotopes are cleanly resolved and have excellent statistics. The mass resolution which we obtain ranges from 0.12amu for carbon to 0.30amu for iron nuclei. In subsets of the data that are restricted to smaller incidence angles (e.g., <45°) the iron mass resolution improves to ~0.25 as expected. This excellent mass resolution, combined with the large collecting power of CRIS, is expected to provide significantly improved knowledge of the isotopic abundances of galactic cosmic rays and should enable us to test models of cosmic ray origin, acceleration, and propagation.

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